A survey of the wind energy resource of Cornwall to examine the influence of settlement patterns and topography on optimum wind turbine size and disposition

Thesis

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A SURVEY OF THE WIND ENERGY RESOURCE OF CORNWALL TO EXAMINE THE INFLUENCE OF SETTLEMENT PATTERNS AND TOPOGRAPHY ON OPTIMUM WIND TURBINE SIZE AND DISPOSITION

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ABSTRACT

The introduction of wind turbines has led to complaints about noise, domination and radio frequency interference from neighbouring properties. The aim of the thesis was to determine how the pattern of rural settlement and topography influences the gross technical resource, and how this resource is affected by various combinations of wind turbine size, type and cluster layout.

The work consisted of examining in detail every possible site in Cornwall and every large site in England and Wales. This involved establishing a computer data base where each location was described by over three dozen relevant site characteristics. In determining mean annual site wind speeds at hub height the data from twentysix meteorological stations and the results of over fifty Tala kite ascents were used to calibrate four predictive models for site wind speed and to choose the best one for this thesis.

Five noise prediction models were tested against field results for twentytwo wind turbines. All the models were found to be inaccurate and a new prediction method with an accuracy of +/- 3dB(A) was developed. A public perception survey of over sixty households situated near six UK wind turbines, and an examination of the way in which the 1974 Control of Pollution Act and planning policies are put into effect, both further defined acceptable environmental criteria for wind turbines. Noise and dominance were found to be the most serious restraints, whilst radio frequency interference eliminated over 40% of potential sites.

The thesis shows that the resource is inversely related to wind turbine size. In Cornwall, the technical resource is 2.5MW for multimegawatt machines rising to 1535MW for quiet machines of 17m to 19m diameter.

CONTENTS

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LIST OF ILLUSTRATIONS

Frontispiece
The author's 145kW Wind Turbine at Treculliacks, Constantine, Falmouth, Cornwall.

LIST OF TABLES

DEFINITIONS

Potential Site	Any open aspect site more than 200m from habitation.
Prospective Site	Any open aspect site free of site blockers such as proximity to airfields, or the potential to cause radio frequency interference problems.
Wind District	An area over which there are spread numerous wind energy developments of varying designs and layouts, often operated and run by several different organisations.
Windfarm	A closely spaced group of wind turbines with a common design and operating organisation.

KEY TO SYMBOLS

Symbol	Definition
A	Total blade area (sq.m.)
a	Angle of incidence (degrees)
agl	Above ground level
B	Number of blades
C	Blade chord (m)
c_0	Speed of sound (330 m/s)
c	Weibull scale parameter
D	Directivity
d	Distance (m)
dB	Decibel
$dB(A)$	Decibel A weighting
exp	Exponent
f	Frequency of sound in Hz.
(f)	As a function of
H	Height (m)
h	Angle between source to receiver line (in horizontal plane) and its projection in the rotor plane in degrees
J	Spanwise length of blade element (m)
K	5.1 x 10 exp -7
K_1	Empirical constants
K_2	Empirical coefficient - 3.5
K_3	A frequency dependent constant
K_4	A frequency dependent constant
k	Weibull shape parameter
kV	Kilovolt
kW	Kilowatt
L	Lift force
L	Length (m)
Lpa	The field measurement of sound pressure level in dB(A) reference 2 x 10 Exp -5 N/sq.m.
LwaB	Gearbox sound power level in dB(A) reference 10 Exp -12 watts
LwaG	Generator sound power level in dB(A) reference 10 Exp -12 watts
LwaR	Rotor sound power level in dB(A) reference 10 Exp -12 watts
LwaT	Turbine sound power level in dB(A) reference 10 Exp -12 watts
	Depth of inner boundary layer (m)
M	Mach number
M_c	Convection mach number
MW	Megawatt
m	Metre
P	Mean sound pressure level in far field in dB
p	Density of air kg / cu.m.
Q	Angle in degrees of observer from axis of rotation

R	Maximum radius of rotor (m)
r	Part radius of rotor (m)
r_o	Distance between source and receiver (m)
S	Strouhal number
SPL	Sound pressure level reference 2 x 10 Exp -5 N/sq.m.
s	Airfoil span (m)
t	Trailing edge thickness (m)
U	Freestream wind velocity (m/s)
u	Wind speed
V	Velocity (m/s)
WP1	Windpower & Co (UK) Ltd's prototype 145kW wind turbine
w	Square root of mean square turbulence intensity
x	Observer distance in m
X	Height of bottom of rotor above ground level (m)
z	Surface roughness - the height in metres above surface level at which the wind speed is zero
θ	Angle between source to receiver line (in vertical plane) and its projection in the rotor plane in degrees
ϕ	Angle between vector from source to receiver and its projection in the rotor plane in degrees
δ	Boundary-layer displacement thickness
ψ	Distance from turbine to observer (m)

SUMMARY

Background

Renewed interest in the use of wind energy arose after the oil price rises in the early 1970's. Since then, the primary target of the national programmes and of the manufacturing companies has been to develop reliable products with long lives at a price which makes wind competitive with other forms of energy. Although great progress has been made, this task is still not complete.

The author's interest in wind energy started in 1972 and was stimulated by the ideas put forward in "The Limits to Growth" Meadows et al (1972). Early experimentation with innovative rotor designs such as vertical axis machines and singlebladed rotors was followed by the development of a comprehensive system for the design of wind turbines. This was mostly accomplished during an honorary research fellowship at Exeter University during the period 1974 to 1982 when over three thousand references were used in developing a design pro forma. Williams (1982a). Two wind surveys were conducted in the China Clay area near St Austell. The first lasted from 1979 to 1981 and the second from 1982 to 1984. Williams (1984a). These surveys included the measurement of the change of wind speed with height over various terrain shapes.

The principal features of the selected wind turbine design were fixed by 1980. Williams (1980). These comprised an upwind, stall regulated rotor with three blades, a diameter of 17.5m and a rated capacity of 125kW with a short term overload capability to 145kW. The choice of this diameter of machine was strongly influenced by the belief that an optimum size existed with smaller and larger machines both giving a more expensive output. The detailed drawings and analysis took two and a half years to complete. Williams (1984b). Every aspect of the machine, except the control unit, was designed and specified by the author. The rotor had a novel construction with a main beam of steel reinforced wood saturated in epoxy, with a glass reinforced epoxy aerofoil shell. This was built under the author's direct supervision as was the nacelle, the installation, erection and commissioning of the turbine. It was cleared to run by the South Western Electricity Board on 5th February 1987 and achieved over 99% machine availability during the next ten months before being taken out of service for modifications to accommodate a Department of Energy experiment on stall control. A photograph of the turbine forms the frontispiece of this thesis and details of its specifications and performance are included in Appendix 1.

The Problem Emerges

From about 1978 in Denmark, and 1981 in California, substantial numbers of small to medium size turbines were installed. By 1984, there were various reports of the wind turbines causing television interference - Causebrook and Palmer (1982), noise - Kelly (1981), interference with microwave links - private communication with Danish Telecom (1984), blade throws - Windirections (Oct 1983), bird strikes - private communication with Trinity House (1978) and infrasound - Tucker (1979).

The Wind Energy Group's 25m diameter turbine started operations near Ilfracombe late in 1984. During the following year there were complaints about its noise from nearby residents. This was given publicity on local television and in the press. North Devon District Council's Environmental Health Department then got agreement from the machine's operators that it would not run at night. In September 1985 the author's application for the erection of the 17.5m machine was granted, but only on a temporary basis "to enable the Local Planning Authority to retain control over development which might become injurious to the amenities of the area". Kerrier District Council (1985).

In this way the impact of a wind turbine on its surroundings had in one case almost halved its output, and in the other, obliged the operator to risk capital which would have been sufficient to build about five houses on a structure which had a temporary operating life of only four years.

Both these machines were small compared with the turbines which were being built, or supported, by the national programmes of several countries in Europe and North America. Also, the average size of commercially available machines has risen from 15m in 1982 to about 30m in 1988. Many of the environmental effects were expected to become more severe as turbines got larger.

Were the national plans and commercial trends aiming to provide machines which local councils and residents were unlikely to accept? What exactly were the environmental polars around machines and how did these vary as a function of machine size and type? If the outer limits of these polars had to be accommodated within uninhabited "holes" in the countryside, then what was the range of the diameters of these holes and how did the numerical distribution between large holes and small holes affect the potential energy output for different sizes of machine? Was there any relationship between the position and size of the holes and the sites with the best wind speeds? Was there emerging a completely new factor which would have a decisive influence on the achievable wind energy resource?

Was the pattern of rural settlement going to decide the size and type of machine which would yield the biggest resource? In short, how does geography affect the design of wind turbines?

It is the aim of this study to answer this question.

Methods Used To Solve The Problem

The plan was to survey an area and to describe every potential wind turbine site within it in terms of its wind speed, its distance to habitation and whether or not it was favoured with features which may facilitate the grant of planning consent. Of these, the site's landscape type, as determined by the Local Structure Plan, would be an important criterion.

Then, environmental polars for wind turbines would be derived and their acceptability would be tested by interviewing people who live close to existing wind turbines in the UK. The polars would need to take account of machines of different size and type.

The capital costs of developing the sites with wind turbines would be assessed and the site wind speed would be used to derive a cost per kWhr so that uneconomic sites could be discarded with the remainder ranked in order of merit.

Finally, various policies for the implementation of wind turbines would be applied to the sites. For example, these would range from putting the largest machine which was practicable on each site, to deciding to have all machines of the same size on all sites, from asking for the maximum capacity per site irrespective of machine size, to laying down a minimum installed capacity for each site. The results would show which machine and deployment policy would give the maximum resource within defined environmental criteria.

If the area taken for this study was only a few square miles then the results would be of very limited value. If the area was so large as to encompass a continent then not only would the project be unmanageable, but the results could well be distorted by settlement patterns which were not representative of those in the UK. It was decided that the area under study should be sufficiently large to offer the prospect of siting several hundred machines so that the results of the study would cover a sufficiently big potential market to justify the establishment of a wind turbine production facility. In this way the results of the investigation would be of direct and practical use in developing wind energy in the UK.

In a preliminary map study of the UK at a scale of 1:250,000 it was found that Cornwall had 777 sites and the entire UK over 10,000. Williams (1982b). Moreover, the number of sites per square kilometre for Cornwall was similar for most of the west of England and for much of Wales except for those high, wilderness areas which were above about 1200 ft above sea level, as well as for large tracts in Scotland at lower altitudes. Here, many different considerations came into play. These related to the difficulties of access, the sparse distribution of existing power lines as well as the responsibility for proposing the siting of wind turbines in landscapes where man's handiwork lay lightest upon the surface.

Cornwall would offer sufficient sites to justify a production run of machines, the county appeared to be typical of much larger areas in England and Wales and represented a working, agricultural landscape where it was believed that turbines would more easily be accepted than in those landscapes which are cherished so highly precisely because they are undeveloped. A different study would be required for those areas. This thesis accepts Cornwall as its area of study.

Work Done In Solving The Problem

The wind speed investigations included a review of previous wind surveys and the existing meteorological records, it supplemented the historical data with a measurement campaign on six further sites, it selected a long term master meteorological station, measured the change of wind speed with height on over fifty occasions, tested the utility of three mathematical models for the prediction of wind speed against the field results for twenty seven measuring locations, and calibrated the best model against the measured data.

In defining the noise polars for wind turbines the five existing turbine noise prediction codes were tested against the field data for twenty two machines and all of these models were found to be in error. A new, empirically based model was developed and found to have acceptable accuracy. Noise attenuation with distance was measured on the author's machine and compared with the literature references. Ambient noise levels were measured at thirteen locations and the cumulative effect of more than one machine was studied. District Council noise criteria were established, as was the public's reaction to turbine noise, the action levels for the issuing of noise orders under the Control of Pollution Act 1974 and typical compensation levels paid to householders by statutory undertakings under the Land Compensation Act 1972.

All the zones within which radio frequency interference could be caused by wind turbines were mapped and sites within these zones were deleted from further consideration.

Environmental polars or siting conditions were established for blade throw, domination of the machine above surrounding habitations, flicker and bird strikes.

The public reaction to wind turbines from people who had no experience of them was assessed from seven literature sources which gave results of previous public perception surveys. We carried out a survey at 62 properties in the UK. These were the habitations which were closest to the author's machine at Treculliacks, the wind turbine on Lundy, WEG's machine in North Devon and the three machines on Orkney.

Wind turbine ex-factory capital costs were assessed by getting commercial quotations from thirteen manufacturers each of which had already sold turbines to a utility. These costs were broken down into component parts both from suppliers quotations, the analysis of costs of Windpower's machine and from the details of three larger designs. Beyond about 40m diameter, modelling techniques and the trend lines of the component costs were used to estimate prices. Grid connection costs were based on the average price for all the prospective sites in Cornwall and installation costs were derived by quotations from crane hire companies. The turbine manufacturers gave estimated foundation costs and costs for delivery of their machines to Cornwall.

The author's machine's output power (kW) as a function of ten minute means of wind speed were used to derive the annual output by matching the ten minute means to hub height wind speeds as derived from the wind survey and the measured Weibull distribution of wind speed throughout the year. The method currently used by the utilities for project financial appraisal was applied to the predicted kWhr income, capital costs, operating and maintenance expenses. This exercise was repeated for wind turbines backed by diesels.

3500 potential sites were assessed, largely by map studies, and over half of these were eliminated by site blockers of various kinds.

The remaining prospective sites were analysed in terms of separation distance to habitation, landscape type, topography, connection distance to the electrical distribution network, and whether or not the site was registered as an agriculturally less favoured area.

The achievable resource in Cornwall was measured by applying nine different policies for implementing wind turbine development in the county in order to find the most efficacious method.

The value of the wind turbine's output both to the CEGB, the SWEB and independent cogenerators was assessed both with, and without, firm standby capacity.

Finally, the results of the study were used to compile a plan for the staged implementation of wind energy in Cornwall.

Results

The wind survey gave a long term mean annual wind speed of 7.52m/s at 25m above ground level for all the sites. Mean annual speeds ranged from 6.5m/s to over 9m/s. The best three hundred sites averaged 8.45m/s.

Noise is the most serious impediment to wind energy exploitation in Cornwall. Noise emissions increase proportionately with turbine swept area. Turbine sound power levels rise from about 90dB(A) for machines of 15m diameter, to over 112dB(A) for 91m diameter machines. Cornwall has low background noise levels recorded at between 21dB(A) and 27dB(A) near typical sites and the existing noise criteria of District Councils mean that a negligible number of sites in the county could be developed with state of the art machines. The problem is soluble if machines are designed to be quiet and are limited to less than about 22m diameter.

Radio frequency interference problems eliminated about 1000 locations out of the total of over 3500 potential wind turbine sites in Cornwall.

The following standard satisfies all the environmental polars around wind turbines:

In an inner zone of 2 diameters there shall be no habitations, nor any roads, paths or any area which is normally frequented by the public.

The outer zone is defined as the area within which the turbine can be heard in the downwind sector during normal operating and atmospheric conditions. Here there will be no habitations.

Four fifths of the people who had no experience of wind energy either supported or were neutral to its introduction. This degree of support was maintained by those who had experience of wind turbines unless they had been disadvantaged in their homes by noise from the machine or from feelings of being dominated by it. Then, fourfifths support changed to fourfifths antagonism.

When installed machine costs are further corrected both for array losses and the increase of wind speed with height, then there is little change in the cost of energy over the range of machine sizes from 15m to 70m diameter. However, beyond about 40m diameter this conclusion is based on modelled predictions of capital costs and there is little prospect of these being achieved in the near future.

Using a twenty five year life, 2% operating and maintenance costs, a five percent test discount rate, 2.2p credited for kWhrs sold and a 30% capacity credit, then 64% of the prospective sites in Cornwall are economic rising to 96% with diesel backup.

From an analysis of the sites the average distance from the turbine to the nearest dwelling is 327m, with a range of 200m to 800m. 37% of sites were in class one landscapes; that is in the nationally designated Areas of Outstanding Natural Beauty. 19% of sites were in class two landscapes, or those which have been designated by Cornwall County Council. The remainder were in non-designated areas. 18% of sites were in agriculturally less favoured areas. The average distance to the existing 11kV electricity distribution line was 220m and 92.5% of sites had adjacent downward trending slopes on one or more sides.

<u>The achievable resource for quiet wind turbines is inversely related to individual machine size.</u> This applies down to a diameter of about 15m below which various factors tended to make the resource less viable. <u>This comes about when operators aim to provide the maximum installed capacity at each site and iterate to find the best combination of machine size and number to achieve it.</u> In Cornwall, this resulted in an average size of machine of between 17m and 19m

diameter and about ten machines per site.

If we exploited all the prospective sites with the optimum size and number of machines then the resource would be 1535MW. This would drop to 500MW if we exclude the AONBs and to about 280MW if we also exclude class two landscapes. However, it is not possible to predict how much of the resource might be achieved because we cannot judge at what point the public and the planning authorities will decide that the county is saturated with turbines and calls a halt to further development.

A staged programme of development is proposed:

Stage I 1% of all the potential sites in the county are developed yielding about 50MW of wind capacity. Towards the end of this phase the County Structure Plan licences further capacity based on the experience to date.

Stage II 5% of all sites would give a capacity of 250MW.

Stage III 10% of all sites that give 500MW capacity and this is close to Cornwall's maximum demand of 520MW. 10% of all sites could still be developed and entirely avoid Areas of Outstanding Natural Beauty.

Conclusion

This study has used the field results in Cornwall, and others in the literature, to test the accuracy of the published mathematical models for predicting:

- wind speeds
- turbine noise emissions and attenuation with distance.
- radio frequency interference zones around wind turbines.

None were satisfactory, and the way in which this project calibrated the best of the wind speed models and derived a new empirical method for the prediction of wind turbine noise is a significant contribution to knowledge about wind turbine siting. Equally significant are:

Establishing a value for the change of wind speed with height over hills.

Establishing the set of environmental criteria for wind turbine siting which is shown to be the one most likely to be accepted by the public.

Showing that the optimisation of erection costs, rather than machine size per se, have the most significant effect in determining the lowest cost of energy.

Demonstrating that rural settlement patterns so limit the size, and therefore the connection voltage, of individual windfarms that it is the Area Boards not the CEGB or its successors which are most likely to determine the commercial future of wind energy.

Showing that, for these Area Boards, the idea of wind being credited with capacity on the basis of the statistical probability of it being available for generation is not satisfactory and that some firm generating standby capacity is needed close to the wind turbine site in order for wind to be of value to the Area Boards and for it to achieve viability on the greatest number of sites.

Finally, proving that in certain widespread landscape types like Cornwall's, the size of the achievable resource is inversely related to individual machine size down to about a 15m diameter wind turbine.

The geography of rural settlement patterns and topography emerges as an entirely new factor in determining the optimum design of wind turbines. This result is in clear contradiction to virtually all national wind energy programmes and to the tide of commercial development, both of which favour larger machines and are, ipso facto, seriously limiting the ultimate contribution that wind can make to the country's energy supply.

Summary References

CAUSEBROOK, J. H. and PALMER, H. P. (1982)
"The reflection and scattering of television signals by the blades of large wind turbines." IBA, Winchester,

KELLY, N. D. (1981)
"Acoustic noise generation by the DoE NASA MOD1 wind turbine." NASA CP 2185.

KERRIER DISTRICT COUNCIL PLANNING DEPARTMENT. (1985)
Planning decision 2/06/85/00712/F. Applicant: G J Williams, Medlyn Moor Farm, Porkellis. Site: Treculliacks Farm, Constantine, Falmouth. Grid reference SW 7178 3103. 26th June, 1985.

MEADOWS, D.H., MEADOWS, D.L., RANDERS, J., BEHRENS, W.W. (1972)
"The limits to growth." Published by Earth Island, London, 1972.

TUCKER, A. (1979)
"The art of tilting at windmills." The Guardian p18, 13.12.1979.

WILLIAMS, G. J. (1980)
"The design of the wind turbine." Report 05/GJW February 1980.

"References on wind turbine design." 10/GJW. June 1982 (a).

"Survey of potential market for medium size wind turbines in the UK." 11/GJW September 1982 (b).

"Report on the ECLP wind survey." 15/GJW. February 1984 (a).

"17.5m diameter wind turbine - engineering calculations." Vols I and II 16/GJW April 1984 (b).

"17.5m diameter wind turbine - The engineering drawings." 1984 (b).

1. INTRODUCTION

Abstract

Only about a third of the energy flowing in the wind is captured by wind turbines and made available to the end user. Small percentage gains in efficiency are in practice much less important to wind energy's viability than the mean annual wind speed of the site, the capital, operating and maintenance costs of the installation, its lifetime, the net credit for output sold and the availability of the machine to generate.

Historically, Cornwall had fewer wind machines for a county of its size than many other parts of England, but what it has lacked in numbers it has made up for by innovation. The first recorded windmill was built in 1296 and some of the corn grinding mills had extraordinarily long lives lasting several centuries. One of the first houses ever to be lit by wind power appears to have been at Redruth, the county was host to one of the UK's first vertical axis machines and to one of the earliest methods of automatic rotor speed control. In 1988 there are about 170 wind machines in the county. Most of these are in disrepair.

1.1 Wind Turbine Characteristics

Wind turbines vary in size from those with rotors a few centimetres across to those of one hundred metres in diameter. Although there are many types of machine (Figures 1a and 1b,) wind turbines for grid-connected electricity generation share three features: first, some arrangement of blades which rotate at varying or fixed speeds under the influence of the wind; second, a gearbox which increases that speed of rotation to one suitable for the electric generator, and third the generator itself which is connected to the distribution system in a similar way to an electric motor. Whereas a motor is driven by drawing a current from the main supply in order to rotate some attached load, in a wind turbine the mechanical energy from the blades turns the motor, which then acts as a generator and exports current to the grid where it is distributed to feed the nearest electrical load.

Of the gross kinetic energy in the flowing mass of air, Betz (1919) has shown that only 16/27ths is available to be turned into mechanical energy because of the slowing down of the air stream as it approaches the rotor. The drag of the aerofoils, energy losses over the tips and roots of the blades and losses arising because the entire air stream is made to rotate slightly by the rotor, mean that in practice only some 40% to 50% of the gross energy can be used. About 2% is then lost in the gearbox (3% for a three stage gearbox) and another 6% to 12% is lost in the conversion of mechanical power to electricity. Some of this electricity is consumed at the turbine site in running hydraulic or pneumatic pumps for braking and control of the machine, to turn the machine to face the wind, for ventilation and to prevent condensation inside the generator when it is idle. Rotor losses are highest when the wind turbine is operating away from its design tip speed ratio (tip speed ratio is the speed of the blade tips divided by the wind speed measured far upstream of the rotor. This ratio normally ranges from 4 to 10). Drive train losses are most severe when the turbine is operating at part load. Small losses arise in the cable to the transformer which steps up the voltage to that of the local distribution network and in so doing loses another 2% of the turbine's output. Further losses occur in transmission at high voltage with another 2% lost as the voltage is transformed down for the final user. In this way, some 43% to less than 33% of the instantaneous power in the wind is eventually utilised.

Types of Wind Machine.

Horizontal Axis

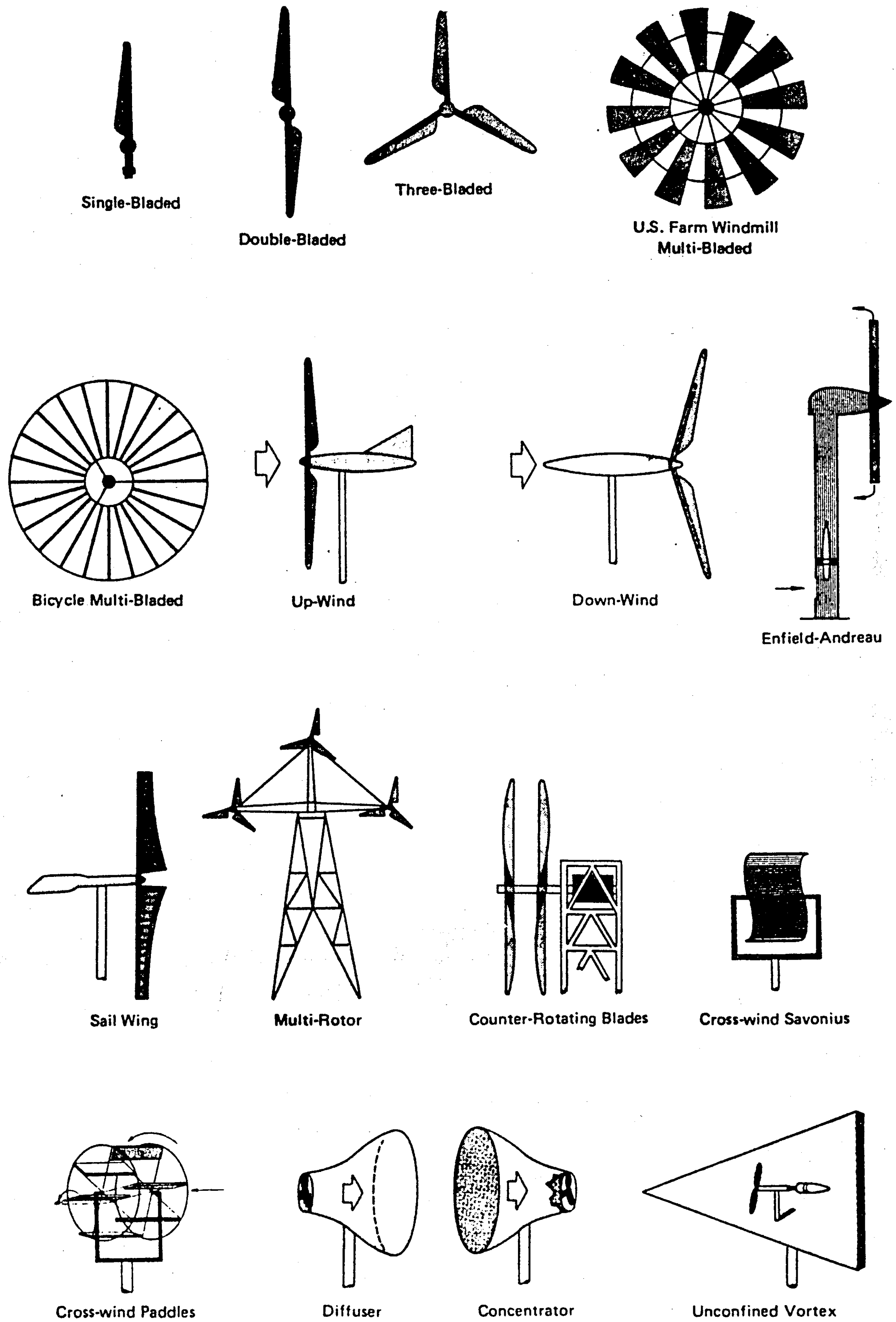
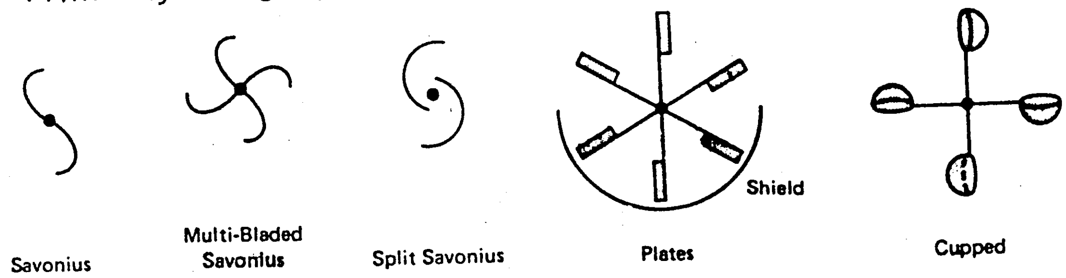


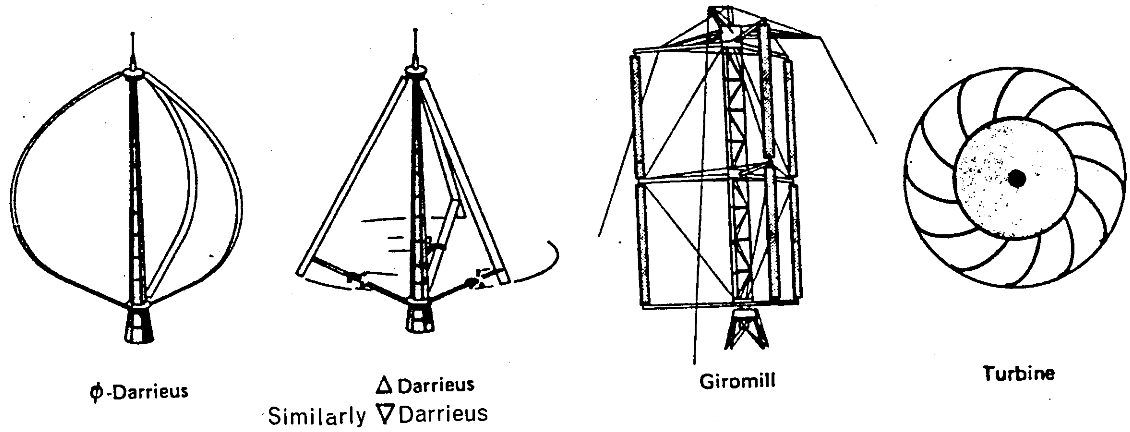
Figure 1a

Vertical Axis

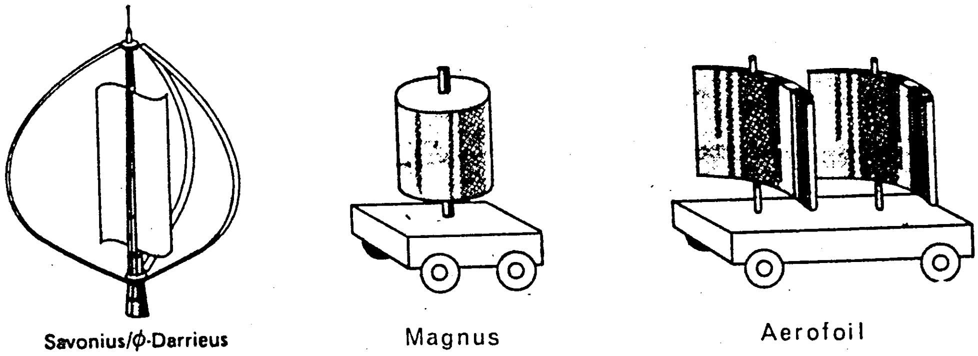
Primarily Drag Type.



Primarily Lift Type.



Combinations



Others

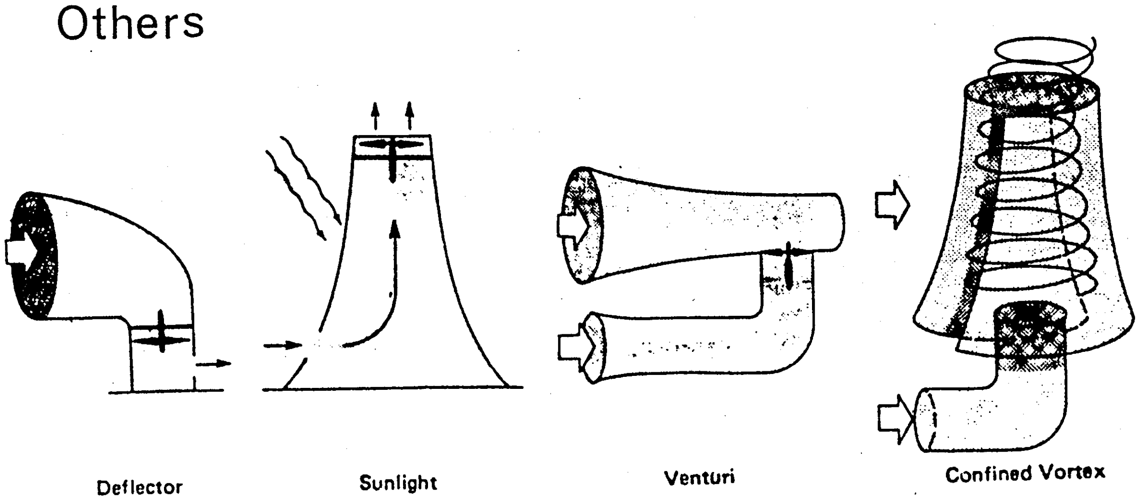


Figure 1b

Although turbines are often referred to by the nameplate rating of their generator, the variability of the wind means that this output is usually achieved for less than 15% of the time. Over a year, a 100kW wind turbine which was constantly available for generation would output the equivalent of between about 20kW and 30kW on a continuous basis. The actual level will depend on site mean annual wind speed. Actual output expressed as a percentage of nominal output is the load factor. In the case of wind turbines it is lower than coal or nuclear plant which output up to 90.5% and 67% respectively of their nameplate rating averaged over the year. The load factor of the national electricity supply system is 55.2%. Electricity Council (1986).

The power in the wind varies as the cube of the wind speed, so a site with a mean annual wind speed of 7.3m/s has a gross energy potential double that of a site with one of 5.8m/s. Site wind speed has a dramatic effect on viability and the ability to find good sites and forecast with accuracy their production is at a premium. The major proportion of a turbine's running costs is the repayment of the capital needed to build the plant. Therefore, capital cost and the rate at which output is credited to the machine, as well as the length of time it is actually available to operate are critical factors in determining its success. In practice, these issues are much more important than a few percentage points of plant efficiency.

1.2 Historical Context

1.2.1 Wind Versus Water

There are now 2000 wind turbines operating in Denmark, Windpower Monthly (1988), yet it is still possible to travel from coast to coast and not see a single machine. Therefore, Celia Fiennes may be forgiven for writing in 1695 "saw not a windmill all over Cornwall and Devonshire, though they have wind and hills enough". (Pearce Chope, 1918). There were corngrinding mills in operation in Cornwall at this time, but their number was less than might have been expected in a county of this size. At the beginning of the steam era, when there were estimated to be over 10,000 windmills in England, it is likely that less than 1% of these were in Cornwall. This arose because it was easier and usually cheaper to control the power of falling water than to build a windmill for corn grinding. Cornwall's relatively high rainfall and the raised, central massifs gave rise to well over a thousand watermill sites for corn grinding and these reduced the need for windmills. The windmills were usually found in places where waterpower was not available such as along the coast and beside the drowned valleys of the Fal, Camel, Tamar and Fowey rivers.

The inventiveness of Cornish engineers during the Industrial Revolution has usually been understated. This is also the case with wind energy exploitation where three of the four major historical phases of its development in the county were marked by significant innovations.

1.2.2 Corn Grinding Windmills

The earliest record is dated 1296 when on Michaelmas Day, Roger de Langurthou leased to Roger Carpentarius of Fowey a plot of land "versus molendinum venti". This was probably a postmill. It was subsequently rebuilt as a tower mill the remains of which still stand in the grounds of Fowey Hall. This is documented in H L Douch's delightful book Cornish Windmills (1963) which traces references to a windmill at this spot throughout the intervening period. From 1662 to 1748 it was recorded as being equipped with sails and was apparently in working order. The windmills of this period had two types of rotor: one had four blades with a trellis of wooden laths across which the sails were tied (1c), and the other had six arms to which sails were attached just like the jibsail on a boat (1d). Douch lists over 70 sites. (1e)

TREVENNAL WINDMILL, ST. JUST IN ROSELAND, *c.* 1840.

'To be let by private contract, for a term of seven or fourteen years, from Michaelmas next,

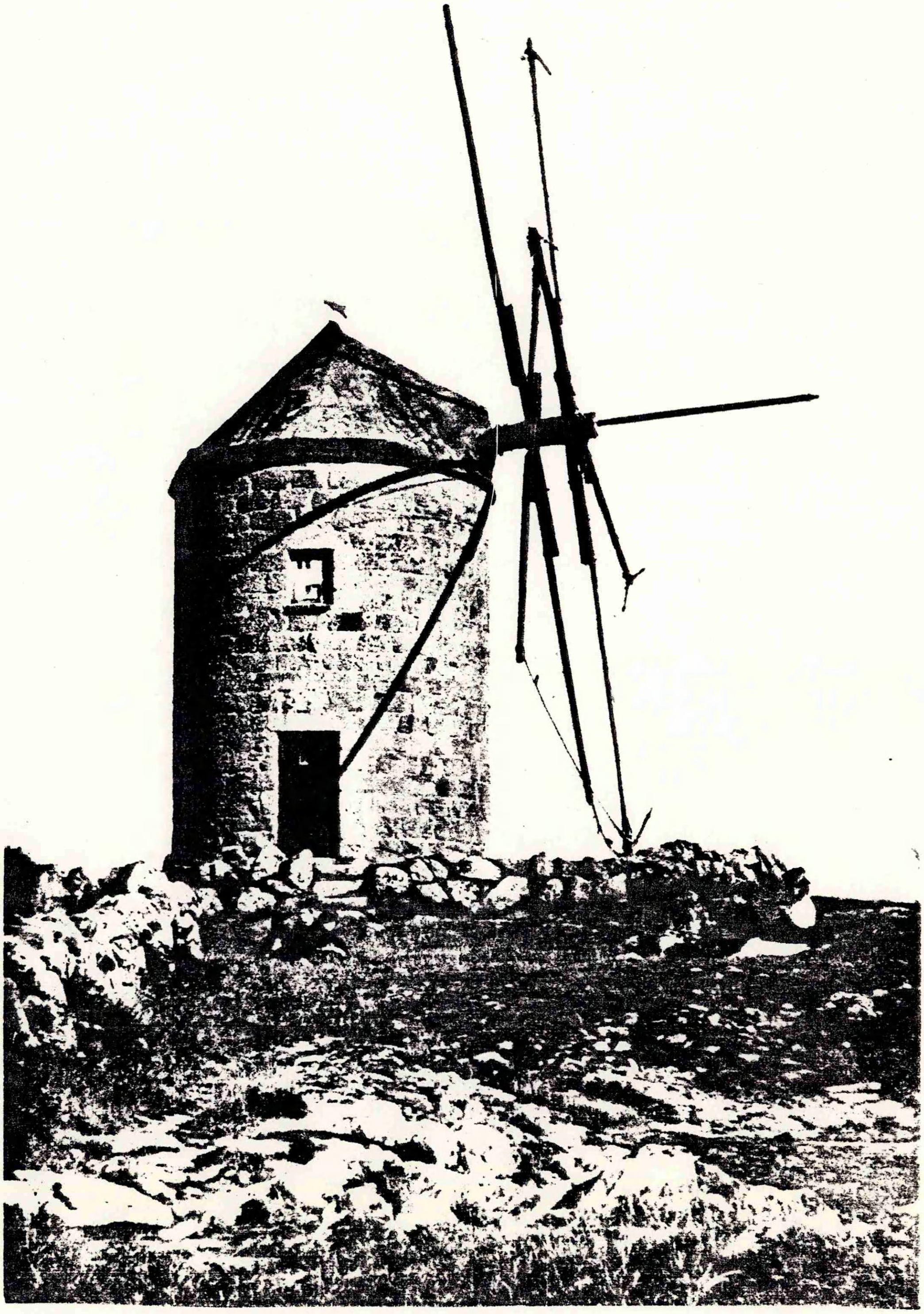
Trevennel Windmill,

Together with the dwelling-house, stable, or carpenter's shop, and two meadows, containing about three acres and two roods of good land, in the occupation of James Borlase.

To treat for the same, and for further particulars, application may be made to James Borlase jun. of Trethewel in St. Just aforesaid, or to Mr. John Dobb of Helston.'

Royal Cornwall Gazette
14th August 1924

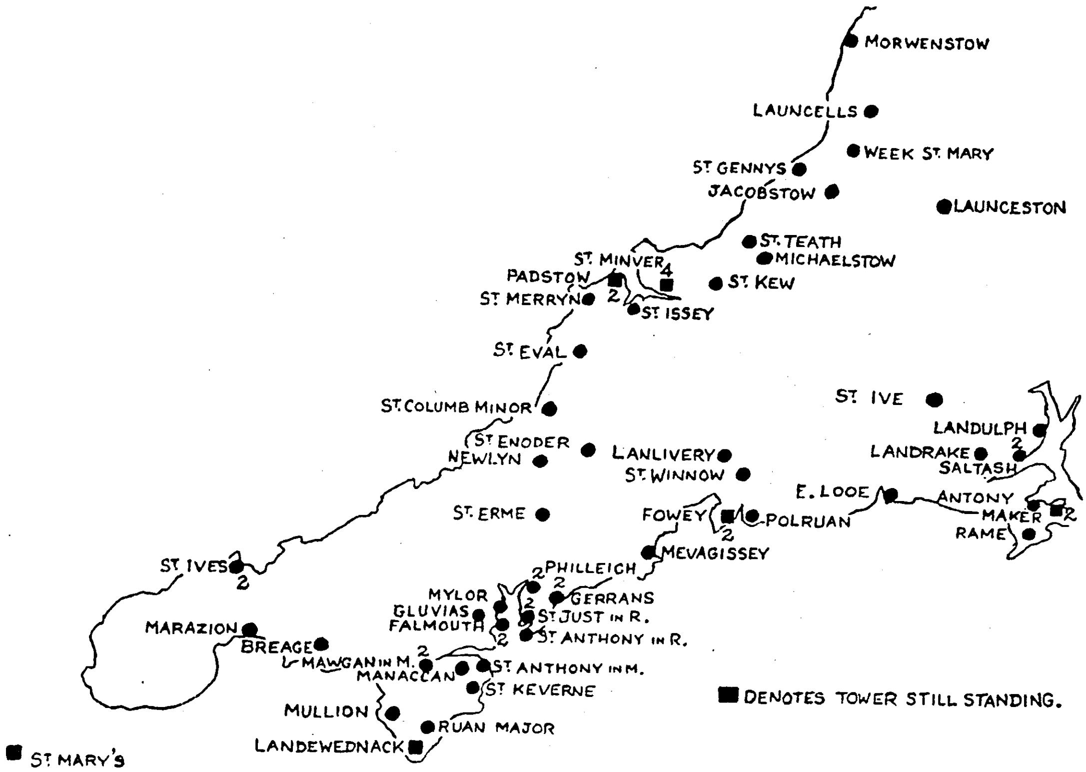
Figure 1c



Windmill On St.Mary's, Isles Of Scilly In About 1880.

Figure 1d

Cornwall.
The Distribution Of
Grist Windmills.



from 'Cornish Windmills'
by H.L.Douch.

Figure 1e

Many of these windmills were leased for terms of up to 99 years. Leases usually included clauses which made the tenants responsible for replacing broken cog wheels, or millstones and repairing sails and items of rigging. In 1597 Rashleigh of Polruan leased his windmill to John Goode and wrote of the terms:
"...he is to reppayre the noggs, runges, and other small worke aperteyning to the myll,... and I am to find sayles, he using them well and from tyme to tyme mending the seyles and restoring at the end such necessaryes as he fyndeth at the mill as bunting, vesells, toll hutches, tubbs, peles, sleepers". (The nogg is a cog, a hutch is a wooden measuring box, a pele is a shovel and a sleeper is a drag for the windmill wheel.)

From about 1772, Meikle and others were credited with various devices for reefing the sails of windmills. However, before these innovations Benjamin Heame, a merchant from Penryn, took out a patent in 1767 for a device which balanced sail area against a counterpoise weight. This was just 17 years after Andrew Meikle had invented the fantail which has been claimed to be the world's first servomechanism. Heame's invention was successfully demonstrated at Wheal Malkin near Penzance in 1789 when "the power and regularity of its working gave general satisfaction to a numerous assembly of spectators who attended the occasion" Sherborne Mercury (Nov 1786). In July 1789 Heame and his partner Treeve were declared bankrupt - neither the first nor last such pattern of events in this trade, but this particular bankruptcy may have had other causes.

1.2.3 Mine Windmills

Windpower was used mainly for pumping water but in 1765 John Rowe of Perransands was granted a patent for a mill to grind ores. In 1797 Richard Trevithick erected a windpump at Ding Dong tin mine of which James Bolitho wrote "Captain Trevithick at that time put a wind engine in the mine, sometimes it went so fast that they could not stop it; some sailors came from Penzance and made a plan for reefing the sails". Trevithick (1872).

What appears to be one of the earliest of the UK's vertical axis windmills was built at Wheal Whidden mine in West Penwith and was offered for sale in 1838. West Briton (16.2.1838). Here it was described as a "horizontal" windmill, which had been built upon a horse whim. A horse whim consists of a vertical shaft with one or more radiating arms to which a horse or horses may be yoked. At the centre there is a wheel around which rope is attached for hauling ore from the mine. From this it is reasonable to suppose that the Wheal Whidden windmill had a vertical axis.

Wind turbines have been very difficult to bring to a state of perfection. This is graphically illustrated by successive entries in the Mining Journal which relate to a windpump at Wheal Vincent which was a tin and wolfram mine on the northern edge of Bodmin Moor.

9th March 1850 ".....our wind engine will be in working order in the course of a day or two: it is a new invention and we must be cautious not to make more haste than good speed. I am certain that it will make a great saving to the mine."

16th March 1850 "Our wind engine works extremely well, with the slightest breeze"

27th April 1850 "Our wind engine is pumping water from the western shaft, and works very satisfactorily."

20th July 1850 "The wind engine is quite useless - a perfect failure and recommended to be taken down and materials used, if of any value"

The mine windpumps died with the collapse of mining in the last quarter of the nineteenth century, but there are two undated photographs which are believed to have been taken at about the turn of the century and which show a very substantial structure of about forty feet in diameter working as a windpump in the China Clay district. (Figures 1f, 1g)

Windpump in China Clay District

Figure 1f

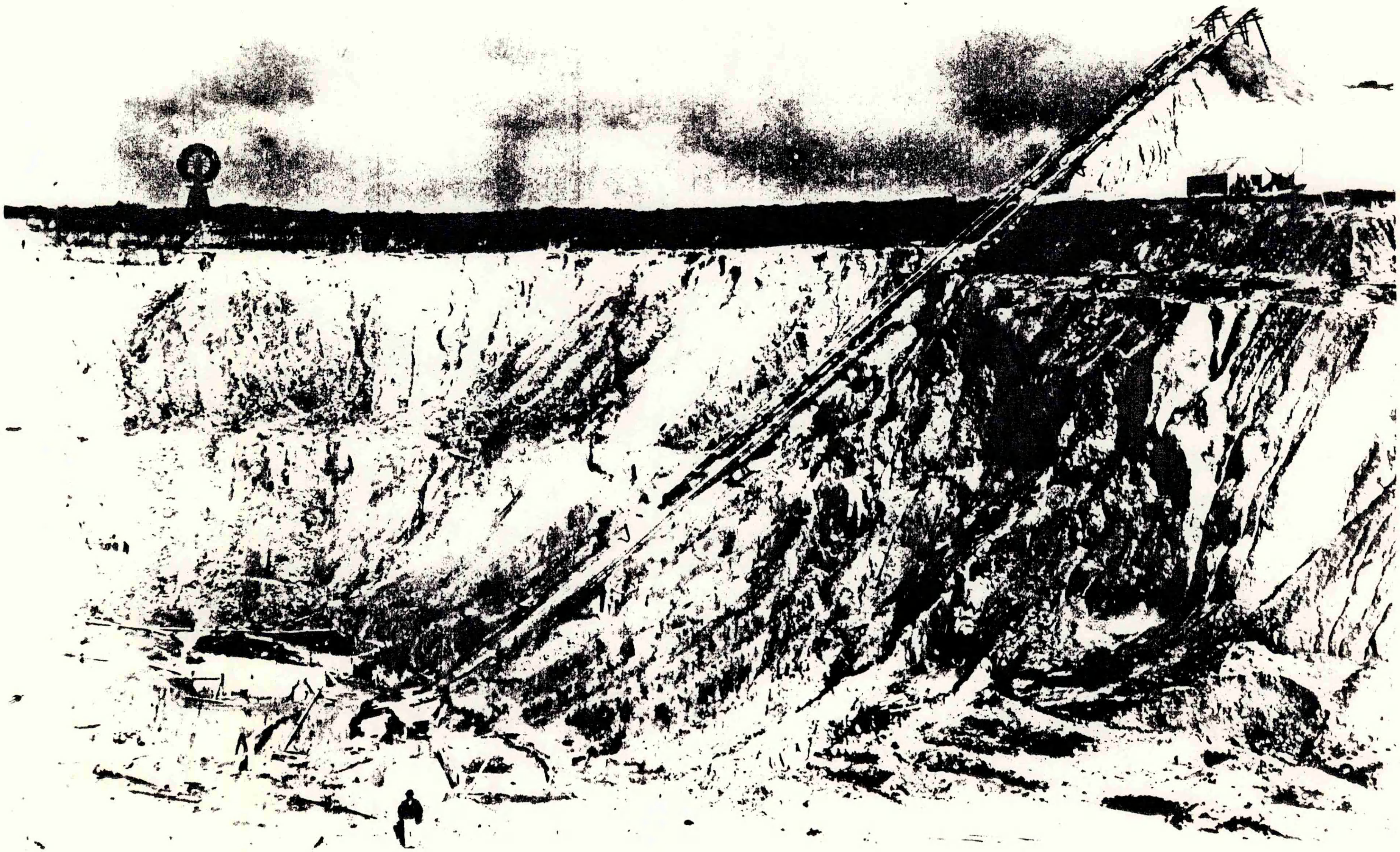


Figure 1g Windpump in China Clay District

1.2.4 Farm Windpumps

From the late eighteen hundreds to the virtual completion of rural electrification in the 1960's, there followed the farm windpump. The Shropshire firm of Climax made over 100,000 of these of which 160 are marked on the 1960 edition of the 1:25,000 map of the county. These had curved steel plates for blades and a spring loaded tail to turn the rotor out of the wind during gales. The rotor worked a cam which raised and lowered a square section steel rod which ran vertically to the water pump in the well or borehole.

1.2.5 Electricity Producing Wind Turbines

One of the earliest reference that has been found to a wind turbine for producing electricity is in the West Briton of May 1892. This describes an 'ingenious windmill' or 'series of windmills' which were built in Clinton Road, Redruth to supply Mr R H Michell with motive power to make electricity. The report says that three times within three years the windmill had been wrecked by gales. In June 1895 the same paper reported another calamity "four times the gigantic wheels of his electric light machinery, towering high above the neighbouring houses, have been blown to pieces by the storms, and the last destruction has not been remedied." If this device started operation in 1889 then it was just nine years later than Sir William Armstrong's first demonstration of hydroelectricity, and shared its birth year with the first ever use of a steam turbine in any public power station, and came just one year later than the grant of patents to Nicola Tesla for his polyphase generators, transformers and motors. Spurgeon (1977). By coincidence, this early example of house lighting powered by the wind was only a few hundred yards from the wall plaque which marks William Murdock's home which was the first house to have been lit by gas.

Darrieus first ran a wind turbine in parallel with a distribution system in France in 1927. However, there appeared to be little further activity in Cornwall this century until 1949 when the Ministry of Fuel and Power commissioned the Electrical Research Association to carry out a hilltop wind survey of the UK and parts of Eire. Six anemometer sites were located in Cornwall. Tagg (1957). No medium size machines were built at this time although the Lucas Windcharger was used at some remote AA boxes, including the one on the Goss Moor, and the same type of machine was used by two members of the artist community living on the moors of West Penwith in the 1950's. The oil price rise in

1974 encouraged a few imports from Switzerland of 2kW Elektro machines and the car designer, Donald Healey, carried out experiments with a similar size machine at Feock and on Perranporth aerodrome.

The erection of the author's 145kW turbine at Treculliacks, near Constantine, Falmouth in 1986 was the county's first grid connected machine (frontispiece). At this time there were a total about 170 wind machines in the county in various states of disrepair. This is about twenty more than the number of disused mine engine houses.

Worldwide there have now been erected over 18,500 grid connected electricity generating wind turbines centred mainly in Denmark (> 2,000), California (> 16,438), Windirections (1988) and the Netherlands (> 160) van den Doel (1986). Denmark's capacity is about 80MW and that of California is 1436MW. The latter capacity was largely constructed during a four year period. These developments came about mainly because of a favourable buy-back price for the electricity sold. None of these areas has such good mean annual wind speeds as Cornwall where the buy-back price and other institutional impediments have prevented any commercial development of the resource.

The Californian turbines are built in groups of closely packed machines (windfarms) in four main areas which tap the largely unidirectional winds being drawn into the hot central valleys of California over the hills from the coast. Many of these windfarms have been built as tax shelters and then abandoned by their owners, giving a very negative impression of wind energy to the casual observer. A very large proportion of the machines have blade faults which are likely to require their replacement in less than five years after being built.

Horizontal axis machines on steel tubular towers with three bladed upwind rotors and varying in size from 55kW to 250kW, or from 15m diameter to 25m diameter, account for the vast majority of commercial turbines. This report is largely based on these characteristics. Research into vertical axis machines has been supported by the Department of Energy over the past ten years, but at the beginning of this study insufficient information was available about their noise characteristics, radio frequency interference and blade throw polars to allow of their inclusion.

Introduction References

BETZ, A. (1919)
"Screw propellers with minimum loss of energy." Nahr. der K. Gesellschaft der Wissenschaften zu Goettingen, 193.

ELECTRICITY COUNCIL. (1986)
"Handbook of electricity supply statistics." p141.

CHOPE, R.P. (1918)
"Some early tours in Devon and Cornwall." Exeter

van den DOEL, J.C. (1986)
"Three years of experience with wind turbines in the Netherlands." Vol 2, p 521 to 526 Proceedings of European Wind Energy Conference, Rome

DOUCH, H. L. (1963)
"Cornish windmills." Truro.

MINING JOURNAL. (1850)
9th March, 16th March, 27th April and 20th July.

SPURGEON, B. (1977-78)
Tesla, The Coevolution Quarterly, pages 64 - 73, Issue 16, Winter.

TREVITHICK, FRANCIS. (1872)
"Life of Richard Trevithick." London.

WEST BRITON. (1838)
16.2.

WINDIRECTIONS. (1988)
Summer.

TAGG, J. R. (1957)
"Wind data related to the generation of electricity by windpower." Electrical Research Association, C/T 115, Leatherhead.

2. WIND SURVEY

Abstract

A search through the existing wind speed records for the county revealed data for twenty one locations as well as two isovent maps. The aim was to provide hub height, long term, mean annual wind speeds for all the prospective wind turbine sites. The problem was that the existing stations did not adequately cover the area of the county and there were very few measurements of the change of wind speed with height over hills. The method consisted of:

(i) Assessing the utility of the existing records.
(ii) Supplementing these records with a new survey at six locations.
(iii) Selecting a long term master station so that short term recordings could be related to the long term data.
(iv) Making over fifty measurements of the wind shear profile.
(v) Testing all of the field data against the mathematical models which predict wind speeds in order to select and calibrate the best method for forecasting wind speeds at the prospective turbine sites.

St Mawgan was chosen as the master meteorological station, an exponent of 0.081 represented the change of wind speed with height over hills. The best mathematical model was found to be a combination of the NOABL program and the methods of Caton and Moore. WASP did not give reliable results. Correction coefficients derived from the testing of these models against the field data improved their accuracy and was used to determine the sites' wind speeds.

The results gave a range of long term, mean annual wind speed at 25m above ground level for all the sites of 7.52 m/s with a range from about 6.5 m/s to over 9 m/s. The best 300 sites had a long term mean annual wind speed prediction of 8.45m/s.

2.1 Wind Survey: The Aim

The aim of the survey was to provide long term mean annual wind speeds at hub height for the size of wind turbines most likely to be used at each of the prospective sites. When the site wind speed was matched to machine performance figures, both the annual output and viability of the site could be determined.

2.2 Wind Survey: The Central Problem

Historical wind speed records were only available for twenty one sites in the county. Some of this data was of poor quality, it did not give a representative coverage of the whole county and was deficient in the hilltop data needed for wind turbine sites. Most of the records had been collected at up to 10m above ground level. This is much lower than the hub height of commercial wind turbines. Two isovent maps were available for the county but these assumed a "flat earth" and ignored both the effect of relief and the influence of local surface roughness on the wind speed at individual turbine sites.

Chapter 13 shows how the final number of prospective wind turbine sites amounted to 1511. As it was only practical to measure wind speed at six sites it was obviously necessary to use a mathematical model to predict the wind speeds at most of the prospective turbine positions.

Two models and one empirical method were selected from a trawl through the literature:

1. WASP - the Wind Atlas and Application Programme. This is the culmination of over five years work by Troen, Mortensen and Petersen at the Riso National Laboratory in Denmark and was first made available in the summer of 1987. Petersen said that the model should be able to cope with the degree of modulation represented by the topography of Cornwall. (Private communication, 1987)

2. NOABL - a model developed by Science Applications Inc in 1979 and designed to predict the effects of large scale orography on steady mean flow.

3. An approach involving the estimation of low level winds from upper air data for Cornwall derived by Bennett, Hamilton and Moore, (1983) then using the measured shear profiles to reduce this data to turbine height. To further correct the results by using Caton's 7% - 9% increment per 100m of elevation, to allow for elevation, and apply Weiringa's (1986) coefficients to account for changes in surface roughness.

These models had very few "bench mark" tests to determine their accuracy.

2.3 Wind Survey: Methods Used

The method consisted of :

1. Assessing the usefulness of the existing site records and isovent maps.

2. Selecting six new locations at which to measure wind speed during 1986-87.

3. Selecting a master meteorological station so that the relatively short term field results made during this survey could be related to the long term record.

4. Conducting field measurements at anemometer heights of 3m, 10m, 15m, and 30m and flying a special kite to measure wind speed (Tala kite) from 10 metres to 75 metres above ground level to determine a representative profile of the change of wind speed with height over hills.

5. Testing the field data against the mathematical models in order to determine and improve their accuracy by applying calibration coefficients.

6. Using the results of 4 and 5 to predict hub height wind speeds at the 1511 prospective turbine sites.

2.4 Wind Survey: Work Done

2.4.1 Assessing The Historical Data

Prior to this survey the author's company, Windpower & Co (UK) Ltd., had field records of wind speed for 21 locations in the county from the following sources:

The Electrical Research Association UK and Eire Survey was conducted between 1949 and 1952. This determined long term wind speeds by ratioing field results to the nearest Meteorological Station:

Table 2.1 ERA Wind Survey

Site	Grid ref	Terrain Height (m)	Instrument Height (m)	Period of Measurement (mths)
Carn Brea	SW386282	200.3	9.15	17
Carn Bean	SW384332	202.7	3.05	11
Watch Croft	SW422358	252.1	3.05	5
Tregonning	SW600300	187.5	9.15	7
Lizard	SW704116	30.4	3.05	16
St Agnes Beacon.	SW710503	191.8.	9.15	18

There is a rapid change of wind speed with height near the ground and records from masts of over 15m in height would have been more reliable.

Table 2.2. Meteorological Office Station Records For Cornwall

St Mawgan	SW873646	106.0	12.2	1967-83	6.26m/s
	SW869649	100.5	10.0	1983-	6.09m/s
Lizard	SW704116	30.4	22.8 or (1)	1953-59, 1961-81.	7.83m/s
Culdrose	SW673256	81.0	23 (2)	>1.1977	5.88m/s
Gwennap Head	SW365217	66.0	10	>10.1977	7.73m/s
Goonhilly	SW718214	99.0	10	12.1982-12.1984	5.83m/s
Camborne	SW629407	88.0	10	>9.1978	5.94m/s
Scilly	SW913120	31.0	20	1.1970-12.1983	6.67m/s

Note 1 Positioned at 18.2m above a building.
Note 2 Raw data is corrected to an effective height of 10m.

These stations all gave the mean wind speed, maximum gust and wind direction for every hour, but Camborne and Gwennap Head only had eight observations per day up until 1985 and 1982 respectively. Camborne is an upper air recording station with four radiosonde ascents each day. The Meteorological Office stations are not situated at locations which give an indication of wind speed at the terrain heights most likely to be used for wind turbines.

Once per day records were also available for Bethel, Penzance, Gulval, Fowey, Falmouth, and Delabole. Only the data from Falmouth is useful because the siting of the other stations did not give a representative record of the area. When the recording positions were checked at each site, one anemometer which had recorded a suspiciously low mean annual wind speed was found to be completely enclosed within a neatly kept privet hedge!

Climatological Memorandum 79 - "Maps of Hourly Mean Wind Speed Over the UK 1965 -1973" Caton, (1976) gives hourly mean wind speeds which are exceeded for given percentages of time (75%, 50%, 25%, 10%, 5%, 1% and 0.1%) over a nominally flat earth. This map is at a scale of 1:5 million and has been prepared from an analysis of all the Meteorological Office station records in such a way that the local effects of surface roughness, topography and anemometer height should have been eliminated.

Roughness was standardised by applying a gust ratio of 1.6 to observed gust speeds in excess of 5m/s, thus producing mean speeds appropriate to this standard roughness condition whilst leaving unaffected the broadscale influences of topographical features. The latter were standardised by reducing the field observations at the rate of 7% to 9% per 100m of terrain height for isolated hills and ridges, but starting at a threshold of 70m above sea level in uplands where the site under examination did not stand out above the surrounding terrain.

This method of deriving wind speeds represents the "surface upwards" approach.

Central Electricity Generating Board

Moore, Hamilton and Bennett have produced a similar scale, "flat earth" map, by analysing the upper air record and using a shear exponent of 0.2 to produce an isovent map for a height of 30m above ground level. This accounts for the change of surface roughness between land and sea, but ignores local roughness, topography and height all of which would have to be re-introduced to estimate long term wind speeds at any one position. This is the "upper air downwards" approach. (Bennett, Hamilton and Moore 1983).

English China Clay International

Unpublished records were compiled by Windpower & Co (UK) Ltd over a two and half year period at five stations of between 182m and 320m height above sea level in the Hensbarrow Clay Area and at Park St Neot on Bodmin Moor. These included shear profiles from a 23.5m mobile mast and a 53.35m tower, as well as data from a "Second Wind" wind logger which gives output as a frequency distribution curve, maxima and minima and standard deviations for wind speed as well as a 45 degree sector wind rose for direction. These records are not publicly available, but were useful for calibrating the final mapped values at nearby and similar locations.

Windpower & Co (UK) Ltd

Recordings were available for Medlyn Moor and for a short period at the turbine site at Treculliacks near Constantine. (Due to changes in the rules governing financial assistance from the Regional Development Grants scheme the proposed site for the wind turbine was moved from Medlyn Moor to Treculliacks shortly before erection, and subsequent wind records are slightly compromised by interference from the turbine.) Both sites had 'run of wind' records. Each hourly mean wind speed was not recorded separately. The cup counter anemometer simply gave an integration of the total flow of wind past the instrument between observations.

Geothermal Project, Rosemanowes Quarry, Herniss, Penryn

Wind speed and direction has been recorded on a strip chart for operations at the quarry. The data did not have sufficient resolution for our purpose. In addition, the site was windshadowed from the west.

2.4.2 1986-1987 Wind Survey

The aims of this survey were firstly to provide new data for areas of the county where no records exist and to sample different hill heights and approach gradients. Three run of wind anemometers were erected on 10m masts at the following sites:

(i) Crowan Beacon to cover the northern part of the Carnmenellis massif.
(ii) Treculliacks to cover the southern part and
(iii) Carland Cross to represent the central spine of the county between Carnmenellis and Hensbarrow.

In addition, masts with anemometers at 10m and 30m above ground level were installed at :

(iv) Trelow to represent the St Breock Downs ridge
(v) Condolden and
(vi) Tresparret near Bude to represent the NE part of the north Cornwall platform.

The latter is a district where no records exist, but which is a potentially rich area for wind turbine sites. The 30m masts sampled the wind every three seconds and gave a tape record of each hour of run so that their output could be compared with synchronous measurements at the Meteorological Stations.

The second aim was to provide further information on the change of wind speed with height, to which end over fifty Tala kite ascents were made. These were each up to 75m above ground level and were carried out at the six new field measurement stations listed above, St Mawgan, Carn Bean, Tregonning, Lizard, St Agnes Beacon, Medlyn Moor, Davidstow and Cold Northcott.

2.4.3 Selection Of Master Meteorological Station

A master meteorological station is required:

a. To provide a long term record so that the field results obtained during the survey can be normalised to the long term mean.

b. To provide input data for the WASP program

c. To provide input data for the NOABL program.

Only the following Meteorological Office stations were considered following:

Scilly. The idea of using an oceanic station little influenced by land/sea effects seemed attractive, but on further examination it was found to have a Weibull shape characteristic (frequency duration of various wind speeds) different from the mainland stations. On these grounds Scilly was rejected.

Gwennap Head. The anemometer tower is placed very close to a steep cliff and is heavily windshadowed from the sector between north and east. Therefore, this station was rejected.

Lizard. This station is no longer in use so it is not possible to examine the way in which the records were compiled. The anemometer was sited over buildings at a non-standard height. There is uncertainty regarding the influence of the buildings in accelerating the wind from some directions and creating turbulence from others. Therefore, this station was rejected.

Culdrose. The same objection applies and many new buildings within 1km of the anemometer have been added over recent years. These would have led to incremental changes in surface roughness characteristics; so this station was also rejected.

Camborne. This site has the advantage of also being an upper air station, but as it only has six years of records it was rejected in favour of St Mawgan.

St Mawgan. The advantages of using St Mawgan as the Master Station include:

a. Continuous records are available from 1968. This is the second longest record for the county.

b. The site is flat and clear of obstructions and hedges for a radius of 400m around the original anemometer position.

c. St Mawgan is midway along the county's length and on the north coast platform. It is likely to be the closest Meteorological Station to wind energy developments.

d. It is also a weather forecasting station so information on the current synoptic situation is available for use with the field measurements.

St Mawgan Station Report

Position of Anemometer Mast:

From 1967 to 5.5.1983	GR873646
Height of mast	12.195m
Ground height amsl	106m
Tower type	Guyed pole
From 5.5.1983	GR86956490
Height of mast	10m
Ground height amsl	100.5m
Tower type	Tower to 8.5m, then pole.

(The Property Services Agency and Meteorological Office Grid Reference of 872649 is incorrect)

Anemometer Type Meteorological Office Mark IVa with an anemograph which is positioned in the control tower building.

Calibration A hand-held anemometer is used daily to check the validity of the anemograph readings. The station anemometer is replaced if these show serious discrepancies. The hand-held anemometer is used on the control tower which is 800m SSE from the station anemometer.

Method of Recording Anemograph Data

Wind speed: the last ten minutes of each hour is examined on the anemograph and a subjective estimate is made of the mean wind speed for this ten minutes. This is then recorded as the hourly mean wind speed. The entire hourly strip chart record is then examined for the highest gust which is entered as the highest gust for that hour.

Wind Direction: the mean wind direction over the last ten minutes of each hour is subjectively assessed from the anemograph and entered as the mean wind direction for that hour.

From the above procedure, errors could arise from:

a. persistently wrong assessment of the ten minute means,

b. the ten minute cycle may not be representative of the hourly mean.

To check for the presence of such errors a new, cup counter, run of wind anemometer was purchased with a calibration certificate from Casella. This was erected at the same height as the station anemometer, but displaced some 20 metres to the east. The records were compared over a 25 day period. This showed that the station anemometer gave a run of wind reading 1% lower than the cup counter from Casella, so it was decided to increment all St Mawgan data by 1%.

The Period Taken For The Base Record Of Mean Wind Speed

Table 2.3 Mean Annual Wind Speeds For St Mawgan

Year	Mean Annual Windspeed (m/s)
1968	5.82m/s
1969	5.77
1970	6.60
1971	5.67
1972	6.23
1973	6.13
1974	7.12
1975	5.82
1976	5.62
1977	6.18
1978	6.23
1979	6.13
1980	6.23
1981	6.49
1982	6.76
1983	6.76
1984	5.93
1985	5.99
1986	6.48

The recorded data from May 1983 to the present was multiplied by 1.0282 to correct for the lower anemometer height over this period. An exponent of .14 was assumed. All the field results were multiplied by 1.01 to correct for the error on the St Mawgan anemometer.

The long term mean wind speed varies according to the years over which it is measured thus:

St Mawgan	1968 - 1986 inclusive:	6.24m/s
	1968 - 1977 :	6.09
	1978 - 1986 :	6.41
	1973 - 1982 :	6.34

This appears to show that the ten years before 1977 were less windy than after 1977. This accords with the findings of the Climatic Research Unit at the University of East Anglia which show that a climatic change occurred in about 1977 with the previous eleven years having unusually low annual mean wind speeds. The question is: in the light of the evidence, which period should be taken as the base? The argument in favour of taking the last ten years on the grounds that we don't know when, or if, another climatic change will occur contrasts with the more conservative view of selecting a time period which bridges the 1977 change so that both climatic types are represented. The latter approach is adopted in this paper since by choosing the period 1973 - 1982 the problem of having to assess the real effect of the change of the anemometer's position and height in 1983 is avoided, and with it, any inaccuracies introduced by attempting to normalise one to the other. This is important since the St Mawgan data is critical for assessment of all the field results and computer derived wind speeds.

2.4.4 Determination Of The Vertical Wind Speed Profile

Wind speed increases with height until a point is reached some 600m to 800m above ground level where the wind is virtually unaffected by the frictional drag of the earth's surface. The relationship between the wind speed at two heights such as the anemometer head height at 10m and the hub height of a wind turbine is usually described by:

The exponent in this equation is principally determined by the thermal stratification of the air and the roughness of the surface over which it travels. If we assume that the air is neutrally stratified (which is legitimate at wind speeds of over 6m/s), then roughness is the chief factor. The way in which it affects the vertical wind speed profile is shown diagrammatically in figure (2a) where the abscissa is a log scale. Weiringa (1986). Where the earth's surface frictional drag is high, the exponent will be greater than where it is smooth, so from this figure we see that:

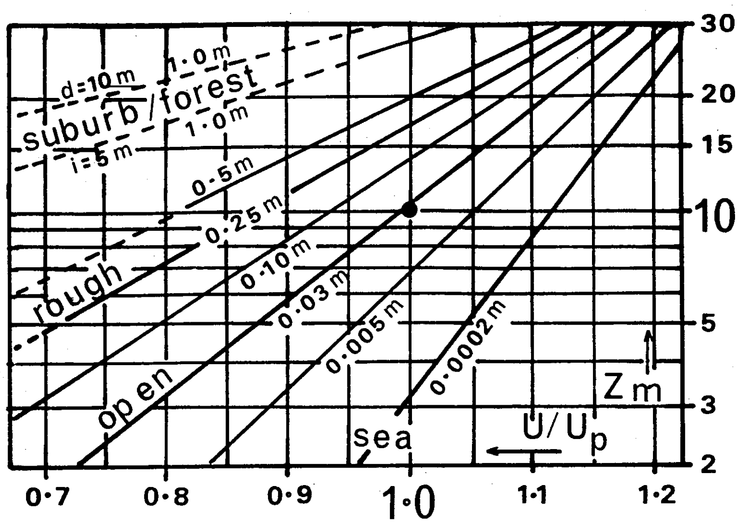
Table 2.4 Shear Exponents (f) Surface Roughness

Surface Roughness Category	Exponent
Sea.	.085
Land surface typical of rural N.Cornwall - very few trees and scattered dwellings.	.14
Rough land surface - many trees and shelter belts (typical of parts of Devon and near the Fal and Helford rivers)	.24

These figures apply to level land. In the absence of reliable field data for hill top sites, many treatises use an exponent of 0.14. There is a substantial penalty for getting this figure wrong. For example, suppose we have long term measurements from a standard height anemometer at 10m above surface level and use an exponent of 0.14 to predict the output from a wind turbine with a hub height of 60m when the actual exponent is 0.08. If the anemometer shows a long term mean of 7m/s then this method will exaggerate the wind turbine's annual output by about 38%.

This is critically important for our survey because of the 1511 sites identified as prospective wind turbine locations, a very high percentage are on hills or ridges for which there are very few reliable wind shear exponents:

Surface Roughness (f) Wind Shear



Nomogram for finding potential wind speed U_p (10m above open terrain with z_0= 0·03m) from observed wind speed U at height Z above nearby terrain, with specified Roughness length z_0 (z_0 values indicated along Graphs).

(Wieringa 1977, 1980)

Figure 2a

Sites with no slopes in any direction	0.94%
Sites with a slope in one direction.	6.56%
Sites with downward slopes in two directions	30.32
Sites with downward slopes in three directions	28.22
Sites with downward slopes in four directions	33.96

Method Used To Determine Vertical Wind Speed Profile

Field anemometry and a literature search (see references at end of the chapter) were used to derive a reliable shear exponent both for estimating wind speeds at various hub heights and to determine at what height rotors should be positioned in respect to the flow over hills. It is not practical to use mobile towers of above about 30m in height, whereas wind speeds are needed over the entire range up to about 100m. For this we used a kite (Tala kite) whose height could be found from the angle of inclination and length of its tether, and from which the wind speed can be derived by a spring balance which records the wind's drag on the kite. From a continuous record of the readings of kite drag on the spring balance the standard deviation of the gustiness of the wind can also be found. All measurements were ratioed to continuous wind speed recordings at 3m and/or 10m above surface level.

Tala kite readings can give false results when taken over short periods of time unless they are taken at times which are representative of energy producing winds. These occur during neutrally stable conditions when cells of displaced air within the moving mass remain in their new position, without further rise or fall, once the displacing force is removed. These conditions are favoured during strong winds which promote thermal mixing and when cloud cover reduces radiative heating. In unstable conditions, strong radiative heating encourages buoyancy and steepens the wind shear gradient at height, whereas thermal inversions flatten the wind shear profile. From observations of cloud cover, surface air temperature and the synoptic chart data, stable and unstable conditions were avoided for Tala kite ascents in favour of neutral conditions.

Over 50 tala kite ascents to heights of between 60 and 100m were made between April and December 1987 at the following sites:

Treculliacks near Constantine
Tregonning Hill
The Lizard

Carn Bean, near St Just
St Agnes Beacon
Medlyn Moor near Porkellis
Davidstow Airfield
St Mawgan Airfield
Trelow
Crowan Beacon
Cold Northcott
Carland Cross.

These results supplemented day long records from six cup counter measurements on a 52m high radio mast on level ground on the Hensbarrow Massif, a 24 day run at a 23.5m mast with five cup counters on West Penrice and three week long runs at the Gunheath and Hensbarrow china clay tips.

Results Of Determination Of Vertical Wind Speed Profile

Three distinct classes of wind shear profile emerged, each representing a different terrain type:

Class 1 Single, isolated "pure" hills

A convenient measure of the steepness of a hill is given by taking the effective height (h) and dividing by the horizontal distance (L) from the top of the hill to the point of half the effective hill height (figure 2b). Typically, these pure hills, (or slopes, since only one direction was tested at a time,) had an h/L of>0.2. Characteristic shear profiles are shown in figure 2c.

These shapes agree with our understanding of the mechanism of windflow over hills. This was taken mainly from Jackson and Hunt (1975). Consider a wind over open level country with an exponent of 0.14 arising from the surface roughness of the terrain (See figure 2c). Then consider a flow in a square cross section wind tunnel for which we suppose that there are no frictional losses along its walls, ceiling and floor. Now if this flow is forced over a typical hill shape placed on the floor of the tunnel then the profile shown in figure 2d will emerge. The sum of these two mechanisms represents what is happening over the top of a real hill where the upper surface of the boundary layer acts to a degree like the ceiling of the wind tunnel. If we sum the profiles from a number of simple hills to smooth out local effects we get the characteristic shape measured by kite and shown by the results in figure 2e. The mean shear profile exponent from the pure hills was found to be 0.081 over a range of from 10m to 60m above ground level.

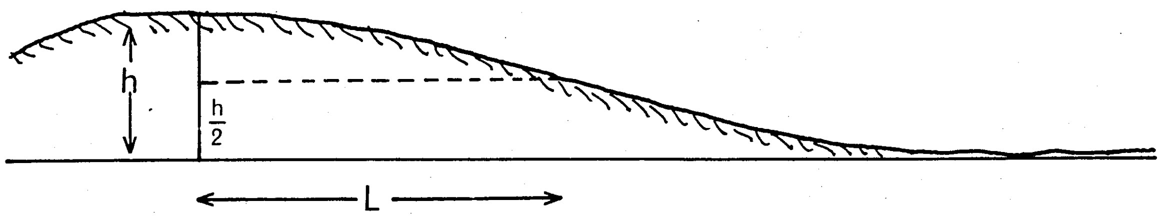


Figure 2b

Derivation Of Dimensions h and L.

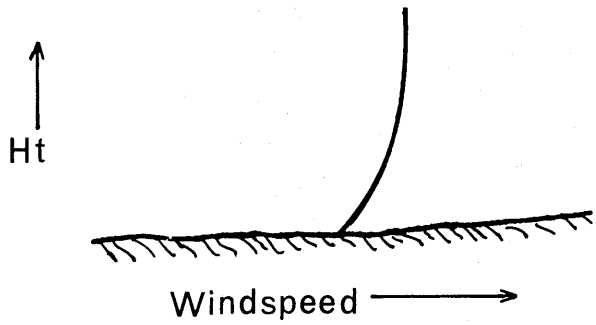


Figure 2c

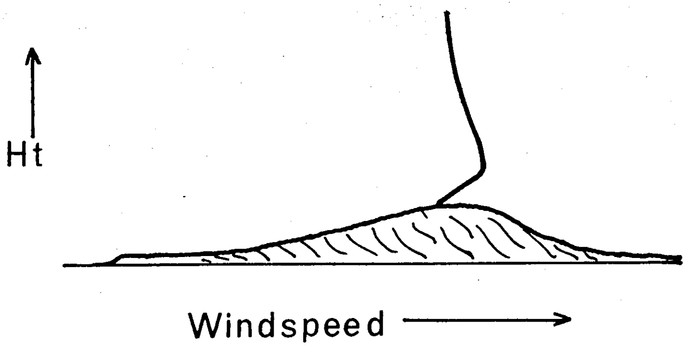
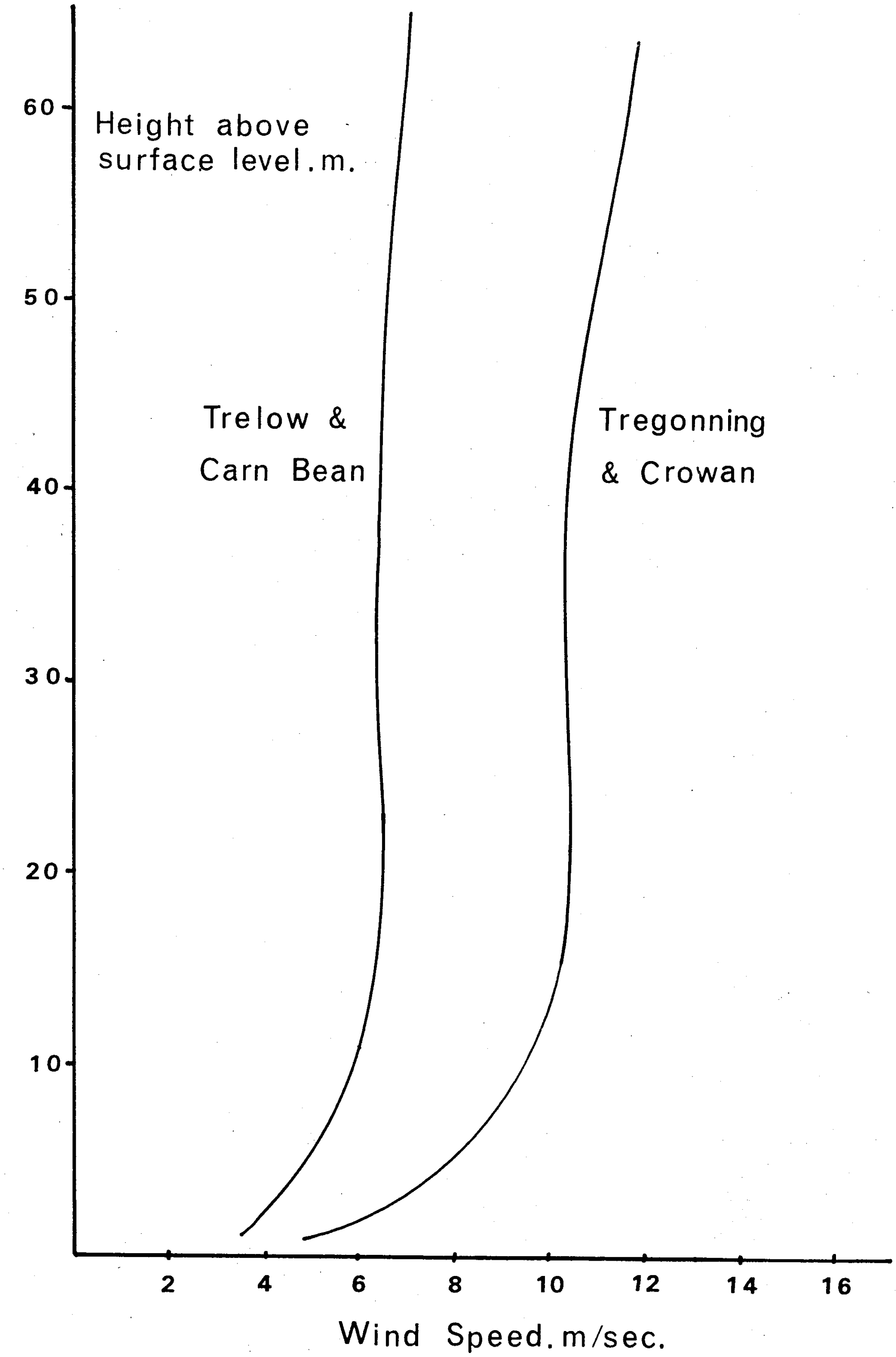


Figure 2d



'Pure' Hill Shear Profiles.

Figure 2e

Class 2 Complex Terrain: i.e. Flow over a hill when one or more hills lie upwind of it. This is the case for most hills rising from the four central Cornish massifs and for many hillocks rising from the indented 100m high wave cut platforms, which flank these massifs. Every result shows a characteristic double bend shape. (figure 2e). We needed to know if this effect arises from the speedup bulge on the upwind hill being convected to a greater height as a second speedup occurs over the hill under study. An experiment was devised to measure the shear profiles upwind of the first hill, over the first hill, between the hills and over and beyond the second study hill. The results are shown in figure 2f.

If we take a mean profile from all the complex hills' experimental results (figure 2g) we end up with a shear virtually identical to that for the pure hills between 15m and 60m above surface level, see figure 2e. If we compare this profile with an exponent of 0.081 the following table emerges:

Table 2.5 Results Of Wind Shear Experiments

Height	Experimental Shear Results Mean Of Complex Hills	Shear Exponent Of 0.081
10m	7.82 m/s	7.82 m/s
20m	8.55 m/s	8.272 m/s
30m	8.55 m/s	8.55 m/s
40m	8.65 m/s	8.75 m/s
50m	8.9 m/s	8.9 m/s
60m	9.0 m/s	9.04 m/s
70m	9.1 m/s	9.15 m/s
80m		9.25 m/s
100m		9.4 m/s

Wind Shear Profiles In Complex Terrain

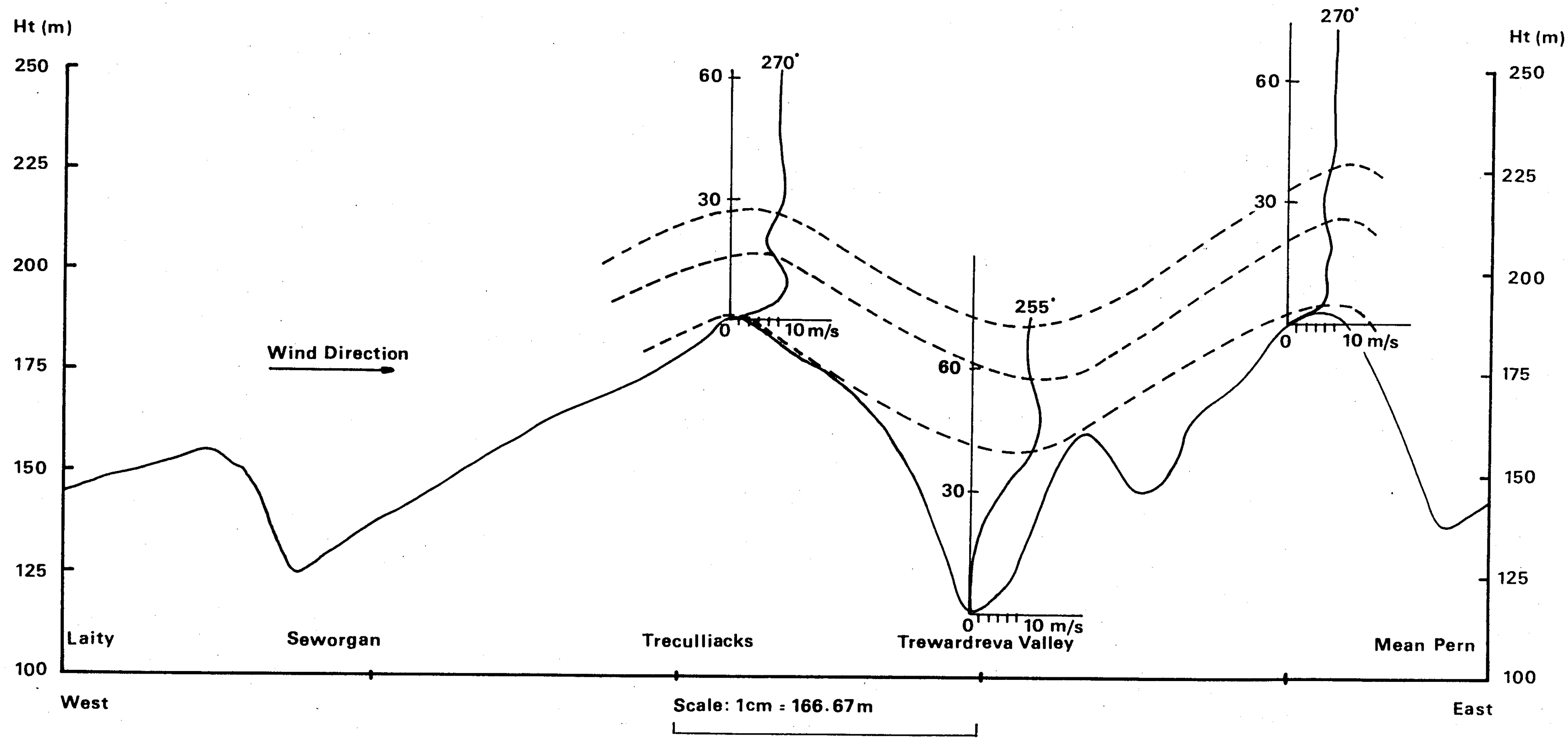
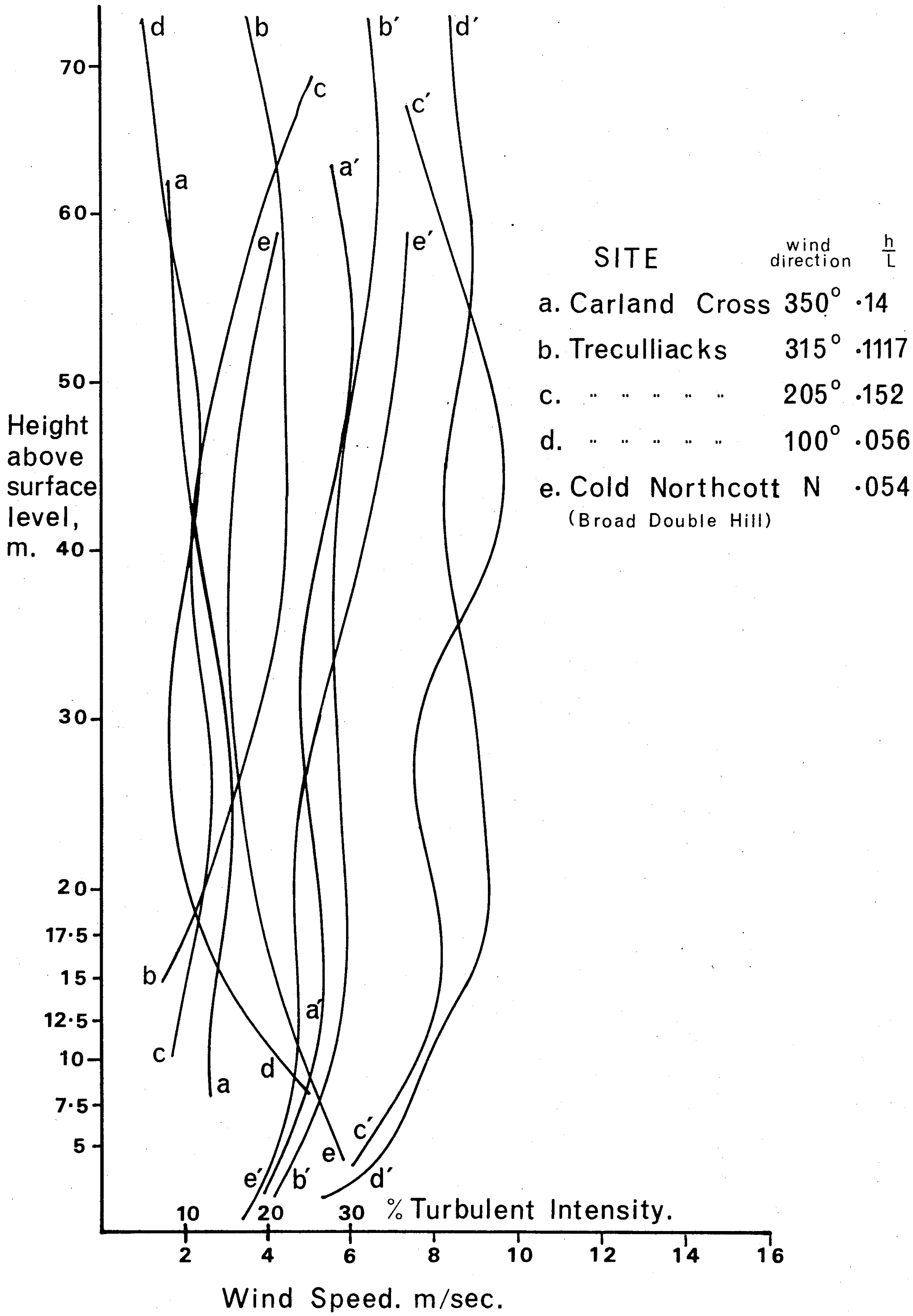


Figure 2f



Double Hill: Profile, Downwind Hill.

Figure 2g

Double Hill Profile Summed Into A Single Composite Shape.

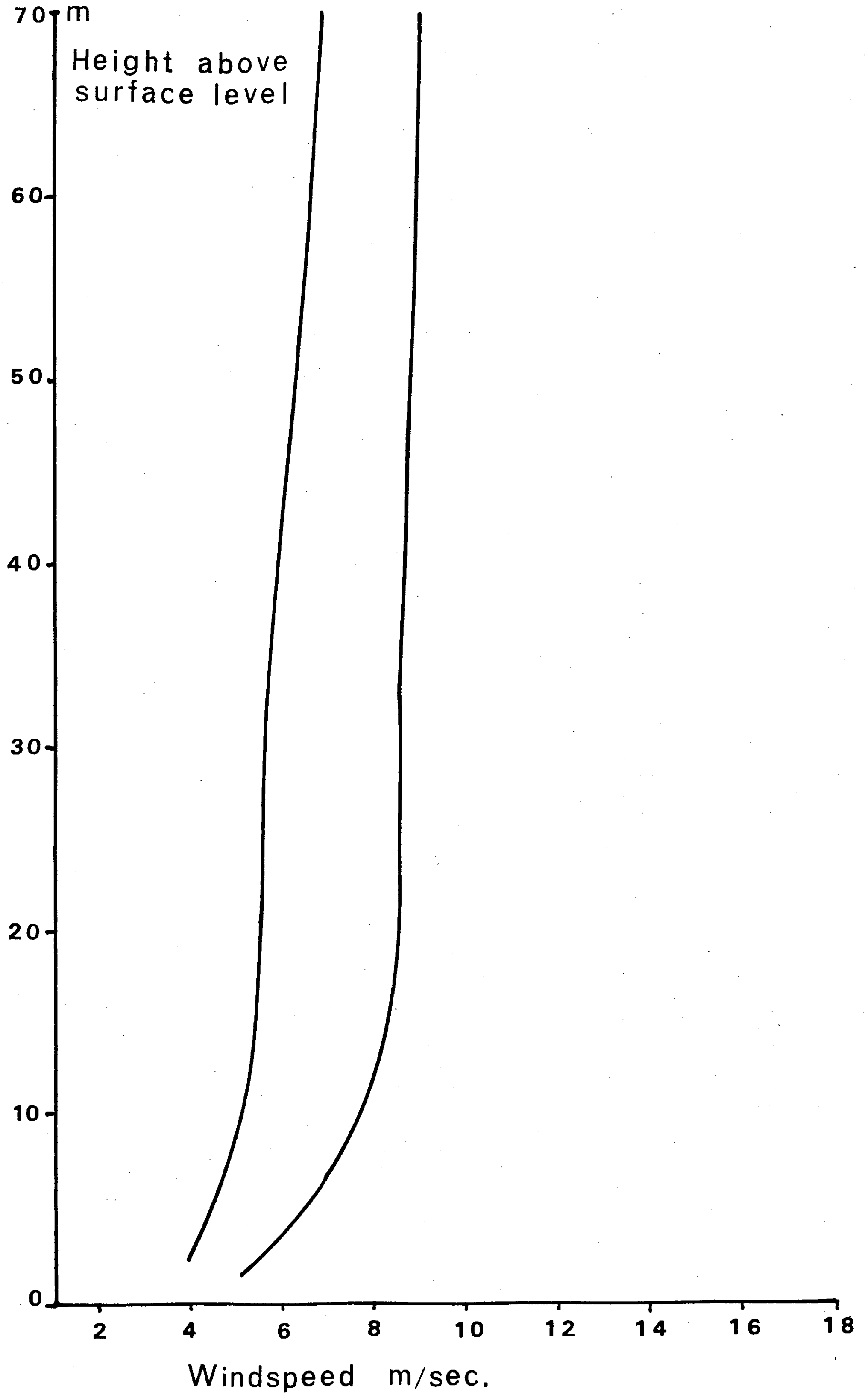


Figure 2h

Class 3 Level Land No characteristic shape emerged from the results for Davidstow and St Mawgan both of which are situated on raised, level platforms. In the absence of any strong forcing effect from the relief, Smith 1967, Jackson 1976, Weiringa 1976 and 1986 have all shown that the shear profile will be responding to changes of surface roughness in the upwind sector. With no good experimental data from this study, but from an abundance of long term data from other sources, it is assumed that the level land exponent is 0.14. However, since virtually no turbine sites are on level land then only the results from Class 1 and Class 2 terrain were material to this study.

Conclusion

An exponent of 0.081 was adopted for hilltop sites for the purpose of this study. This is much lower than that used in previous investigations of this kind: Newton and Burch, (1984), use exponents of between 0.12 and 0.22; Delaunay, (1986) uses an exponent of over 0.1 and Bennett, Hamilton and Moore, 1983, use an exponent of 0.2. This means that hub height wind speeds calculated from 10m or 20m agl anemometers (eg Caton) will be lower than the previous studies indicated, but if the hub height mean wind speeds are derived from upper air winds (eg Bennett, Hamilton and Moore) they would be higher.

2.4.5 To Find The Optimum Height At Which To Locate The Rotor In Respect Of Wind Flow Over Hills

The shear profile graphs (2c-f) show a lower knee below which wind speed falls off at a disproportionately higher rate and turbulent intensity values rise inversely. To place the rotor below this lower knee will lose energy, expose the blades to unnecessarily high levels of turbulence and cyclically varying wind loads. To place the lower rim of the rotor's swept area above this knee gains very little if anything by way of energy or reduced turbulence, at the expense of a more costly tower and the much more expensive cranes needed for installation or maintenance.

If we plot the position of this knee against hill shape as defined by (h/L) and shown in figure 2h we see that the steeper the hill, the lower the knee. An analysis of fifty slopes from a random selection of potential sites showed a range of (h/L) values between 0.04 and 0.1 For the purpose of this survey, 12.5m was adopted as the minimum height for the bottom of the rotor. When it comes to planning an actual installation, the optimum tower height can be chosen from Tala kite ascents for wind from representative directions, or from the graph in figure 2h.

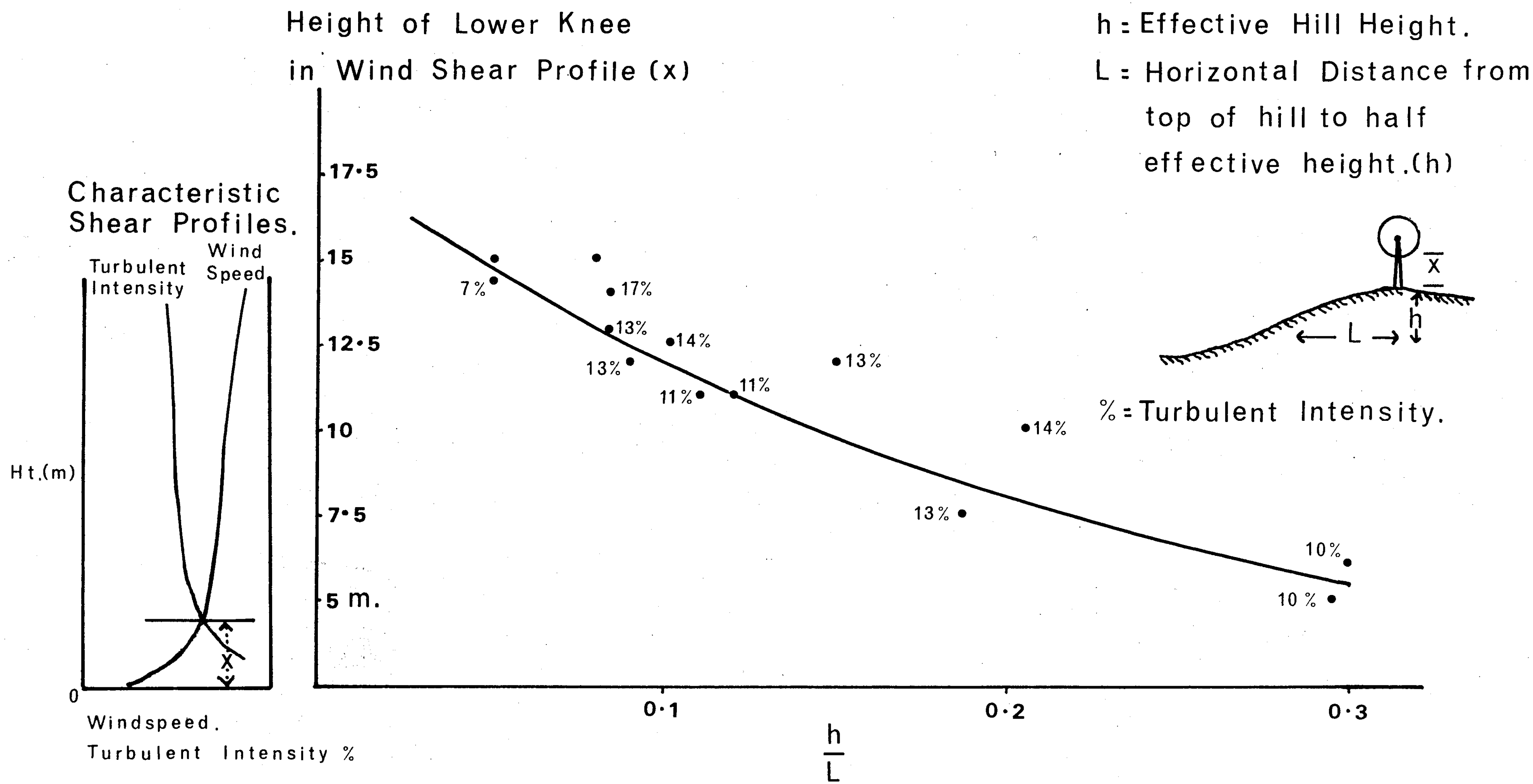
Jackson and Hunt (1979) identify an inner and outer layer for wind flow over hills. In the inner layer of flow the horizontal velocity is the same as the undisturbed upwind velocity at the same displacement above level ground. In the outer layer the perturbed flow is driven by the vertical displacement of the flow by the hill in the inner region up to a point high above the hill where the vertical velocity tends to zero.

The expression which gives the height in metres of the inner layer is:

$$l = \frac{z}{8}\left(\frac{L}{z}\right)^{0.9}$$

The height of the knee in the wind shear profile derived from this survey was in good agreement with the height of the inner layer as predicted by this expression.

The historical wind speed data and the data from the 1987 wind survey have now provided long term mean annual wind speeds at 27 locations. The tala kite ascents have given representative vertical wind speed profiles and guidance on the correct height of the rotor. This information was then used to test the utility of the mathematical models.



To Find Height Of Rotor Above Ground Level On Hill Tops
As A Function Of Hill Slope. h/L

Figure 2i

2.4.6 The Testing Of WASP Against The Field Data

Upper air mean wind speeds change slowly as a function of distance away from some specified location. Winds measured near ground level, say at 10m or 20m above the surface, are related to the upper air winds by the logarithmic law as described on page 2.13. The logarithmic law is conditioned by three factors:

1. The pattern of terrain roughness around the site of interest.

2. Obstacles close to the measuring position which may shield or windshadow the anemometer.

3. The shape of the hill.

If these effects could be quantified then it would be possible to extrapolate from a long term near surface, measuring station (St Mawgan in our case) to forecast its upper air, long term mean wind speed. Now, as this latter value does not change very much within say about 50 miles, we can assume that within this radius the upper air wind speed applies above <u>any</u> site at which we wish to know the long term, near ground, mean wind speed. Then, to find the near ground, long term mean at this new site from the upper air value, we could enter values to account for local conditions of roughness, obstacles and topography. This would be the reverse procedure used to find the upper air winds from the St Mawgan near ground level record.

This "double extrapolation" method is the basis of the WASP programme. It groups topography into five classes. The version released in June 1987 was able to predict wind speeds in the first two of these classes. Cornwall falls into class 2 non-mountainous regions with small scale, smooth, hills and valleys with typical horizontal dimensions of less than about 1km. WASP's suitability for this terrain was confirmed by Riso after their studying of the county's 1:50,000 maps.

Work Done

The St Mawgan data was input to the programme and a trial run was undertaken to see if the program would forecast the long term mean annual wind speed at Culdrose by applying the latter's roughness, orography and obstacles. This it did to an accuracy of better than 2%.

55 sites were visited and roughness and obstacle inputs prepared.

Topography was digitised into the program for 10 sites for which field records of wind speed were available, in order to test further the program's accuracy in conditions of modulating relief. This was in contrast to Culdrose whose plateau like topography was similar to St Mawgan's. The results are tabulated below:

Table 2.6 WASP:Predicted Values Compared With Field Results.

Site	Grid Ref	WASP With Terrain Model	WASP Without Terrain Model
Culdrose	SW673256	-2%	-2%
Lizard	SW704116	-15%	-35%
Carn Bean	SW384332	+26%	-37%
St Agnes Beacon	SW710503	-57%	-60%
Condolden	SW090872	N/A	-33%
Carn Brea	SW386282	-29%	-65%
Watchcroft	SW422358	+17%	-42%
Gwennap Head	365217	+25%	-7%
Tregonning	SW600300	-2%	-58%

- = Underpredicted field results
+ = Overpredicted field results

The program does not allow the user to display the digitised terrain data on the screen. The digitising had been a particularly arduous task and in case inaccuracies had caused program errors, the Ordnance Survey digitised terrain data was purchased for the Carnmenellis area. The WASP program could not accept all of its data points so contours at more than 4km from the sites under investigation had to have reduced resolution. The results are given in table 2.7.

In addition, WASP allows the user to input a standard Gaussian Hill with the long axis oriented as in the field, and the hill half height width is input to indicate the steepness of the approach slopes. This gave the following results:

Table 2.7 WASP: Predictions With Gaussian Hill Option

Site	Grid Ref	Results
Treculliacks OS Terrain data	SW717311	- 9%
Crowan OS Terrain data	SW664351	- 18%
Treculliacks Gaussian Hill		+ 239%
Crowan Gaussian Hill		+ 222%
Condolden Gaussian Hill		+ 214%

+ = Overpredicted field results.
- = Underpredicted field results.

WASP Conclusions

1. The program agrees with the field measurements for the level land site of Culdrose.

2. The predictions for hilltop sites were very erratic.

3. There appears to be a fault with the Gaussian Hill option. Condolden Hill was chosen as a measuring station because it is remarkably symmetrical and Gaussian like. The wide error here suggests a problem with WASP.

A choice has to be made between believing that the WASP data, or the field data, is correct. The field data was chosen as the reliable benchmark for the following reasons:

1. Some of the records were made over many years.

2. All the field station results were ratioed to St Mawgan's long term mean thus largely eliminating the effect of the short term of the measuring period. To achieve the best accuracy, the synchronous measuring station results were grouped into twelve, 30 degree sectors and the wind speed in

each sector was normalised to a roughness value of 0.03 as was the equivalent sector at the master meteorological station with which it was compared.

3. The field results were mutually consistent, whereas WASP was erratic and did not lend itself to the application of empirically derived correction coefficients.

4. Riso are now making alterations to the WASP code in respect of the terrain model. The results were not available during the term of this study so WASP was abandoned.

4.7 NOABL

NOABL is a mathematical model which predicts the effect of large scale orography on mass flow. Imagine the wind blowing from, say, the north over a relief model of Cornwall which is placed on the floor of a wind tunnel. The ceiling of the wind tunnel is provided by the overlying air which tends to limit the degree to which the entire mass flow can rise over relatively small scale terrain features. Assume that the same volume of air leaves the wind tunnel exit over the sea to the south of the Cornwall model as enters it from over the sea to the north. To achieve this, the wind's speed will be enhanced where the air is forced through the narrow gap between the central spine of the Cornwall model and the wind tunnel roof. The narrower the gap, the greater the speedup of the flow. NOABL accepts as input the terrain map of the county and near-surface observations of wind speeds. It interpolates wind speeds from the station data onto a three dimensional grid and then adjusts the flow to be mass consistent over the input terrain. By repeating this process for every 30 degree sector and by characterising the input wind speed frequency and direction, a terrain induced isovent map can be produced from NOABL.

A major problem with NOABL is that, because of computing constraints, the program for an area the size of Cornwall best accepts terrain data at the rate of one spot height for every 2km by 2km of land. This low level of detail means that the effect of hill height, and therefore speedup, is reduced. Secondly, the model does not account for different roughness characteristics in different parts of the county; nor for thermally induced circulations such as sea breezes. It is, like the WASP model, designed to simulate aerodynamic flow variations alone.

The initial vertical scaling of wind speed for NOABL is under user control with a default exponent value of 1/7 or 0.143. As the program solves the problem of organising the flow across the high land such that the same mass of air leaves the area as entered it, this necessarily results in exponents over the high land of a different, usually lower, value. The vertical change of wind speed over representative terrain was measured as part of the survey and is described above so the question arises, how can these field results be best used to strengthen the utility of the model? There are two options:

1. Apply these terrain dependant shear values to the program and make NOABL conform to them over the hills. This was difficult to achieve because the values of the shear exponent derived from the survey did not reach the top of the boundary layer, so this was rejected in favour of:

2. Apply a value of 0.14 for the shear in the approach flow over flat, coastal land and let NOABL then determine the wind speeds at 10m above surface level for the entire area under study before applying the experimentally derived shear values to find the wind speed at the chosen hub height. In this way the reduced effect of the terrain on the flow due to the simplification of the relief by the 2km x 2km sq sample rate is to some extent offset by using the wind speed at a height above the terrain which is strongly influenced by speedup effects. For example, NOABL would show more strongly the effect of terrain on flow at this height than near the top of the boundary layer. This method also allows the user to vary the exponent for each site under investigation in response to any terrain features which are more detailed than those which can be resolved by NOABL.

Table 2.8 The Input Parameters For The NOABL Program

Shear exponent	0.1429
Horizontal cell size represented by a single spot height	2km x 2km
Height of boundary layer above ground level	200m
Height of upper boundary of cells	800m
Minimum vertical cell size	10m
Number of cells vertically	15m
Maximum number of iterations	100m

To check NOABL's accuracy its results were compared with sets of synchronous readings from six measuring stations. The following table was compiled from field results all normalised to a roughness of 0.03. This is the most common roughness value for Cornwall: (Key: -14 = NOABL underpredicts by 14% and +21 = NOABL overpredicts by 21%)

Table 2.9 Reconciliation Between NOABL's Predictions And The Measured Field Results

Sector	000 (North)	030	060	090	120	150	180	210	240	270	300	330
St Mawgan (L)	No error - used as base reference station.											
Culdrose (L)	-43	-13	-22	+43	+3.5	-13	-51	-8	+24	+43	-13	-51
Gwennap Head (C)	-42	-72	-74	-8.5	-18	-22	-68	-61	-4	-8.5	-11	-21
Kehelland (L)	+4	+6	-12	+16	-16	+9	-15	+20	+18	+16	+8	+15
Condolden (H)	+14	+14	+19	-17	+4	-2	+4	+14	+10	-17	+4	-2
Tresparret (H)	-35	Nil	-8	+2	+8	-58	-49	-5	-8	+2	-24	-46
Trelow (H)	-24	-16	-7	Nil	-29	-16	-4	-16	-7	Nil	-29	-16
Mean Sector Value:	-16.9	-1.8	-6	+8.9	-5.7	-16	-23	-14	+7.4	+8.9	-10.8	-20

Overall Mean Error: 11.9%. NOABL tends to underpredict actual wind speeds.

Key (L)= Level land in vicinity of measuring station.
(C)= Coastal site.
(H)= Hill top site.

Notes On Manipulation Of Field Data For NOABL

(1) In the observed data, site wind speeds in Sector 090 at St Mawgan were severely underestimated. The reason for this was that Carnanton Woods, to the east of the anemometer, was providing the instrument with more shelter than allowed for by the roughness classification coefficients. Therefore, the reverse direction - 270 degree - speedup values were used for this sector.

(2) From table 2.9 it is obvious that Gwennap Head is consistently underpredicted by NOABL. This is probably due to the higher thermally induced wind speeds pertaining at the coastline itself, rather than to a deficiency in the terrain model. To avoid biasing the calibration, this station was omitted from the mean sector values.

(3) Each sector run for NOABL over the whole county was corrected according to the mean sector value shown in the table 2.9. Then, the 1971 to 1982 sector to sector record for St Mawgan's wind speed duration (run of wind) was applied to get an roughness-normalised, terrain-induced, mean annual wind speed at ten metres above surface level. These results

were then integrated and an isovent map of the county was prepared for further comparison with 20 field stations. The field stations had their long term, mean annual wind speeds corrected to a common height of 10 metres above ground level.

The following table shows the accuracy achieved by NOABL after calibrating its output as described above:

Table 2.10 NOABL: Percentage Error Between Predictions And Field Results After Calibration Of The Model

Station	Error %	Type Of Error
St Mawgan	Nil	
Kehelland	- 1.3%	
Goonhilly	+ 7.3	
Treculliacks	- 3.2	
Crowan	+ 0.5	
Carland Cross	- 9.6	
Lizard	- 29.4	A
Gwennap Head	- 23.0	A
Culdrose	+ 0.2	
Trelow	- 3.0	
Condolden	+ 7.2	
Tresparrett	- 3.6	
St Agnes Beacon	- 50.5	A and B
Carn Brea	- 54.7	A and B
Carn Bean	- 10.0	A and B
Watch Croft	- 9.9	A and B
Tregonning	- 34.7	A and B
West Penrice	+ 1.0	
Melbur	- 0.8	
Blackpool	+ 0.9	
Park St Neot	+ 8.3	

- = NOABL Underpredicted the field data
+ = NOABL Overpredicted the field data

A Errors: These appear to arise on account of the higher, thermally - induced wind speeds which occur at or very close to the coast and which are not modelled by the NOABL program.

B Errors: These appear to arise when the relief feature is too small to show on the NOABL terrain model which only accepts one spot height for every 2km by 2km square. In this size of mesh Tregonning Hill and St Agnes Beacon completely disappear.

When A and B cases are deleted from the sample the remaining mean accuracy is 3.6% but with a range of +/- 8%. The long term mean annual wind speed predicted by NOABL at 10m above ground level appeared to be suitable for use in the survey after making corrections for:

1. Coastal Sites. Figure 2i was used to model the increase in wind speed near the coast. It is based on the long term means of Gwennap Head, Lizard, Scilly, Culdrose and St Mawgan. It does not include sites with steep sided hills in the coastal littoral such as St Agnes Beacon. To improve on this accuracy a new field survey would be needed.

2. Small Hills. Where hills were too small to be seen on the NOABL mesh, interpolation was used based on the nearest field data applicable to the hill's h/L value.

3. Roughness. The results assume the surface roughness surrounding each station to be 0.03. This is a reasonable mean value for Cornwall. To gather and record site roughness for 55 sites took about 6 weeks and it was not possible within the project's timescale to cover the remaining 1456 locations. Therefore, when there is interest in a particular site the estimated long term mean from this survey will have to be corrected to allow for the effect of sector roughness and local obstacles.

Future Application Of NOABL

NOABL has been shown to be a useful tool in identifying the areas with the best wind resource when used on a 2km grid for a region the size of Cornwall and West Devon. Its accuracy can be improved for detailed surveys by calibrating it to existing meteorological stations and to anemometers erected for the purpose and run for three or four months. Once a few relatively small, say 5km by 5 km, areas have been selected for potential exploitation it would be instructive to rerun NOABL on a much more detailed terrain mesh of say one spot height for every 50 or 100 metres square. The output could be checked against an intensive array of anemometers (at 20m agl). This is essential in the effective micrositing of wind turbines where we need to know how far turbines can be sited away from the hill top and what power losses occur in such a situation in climates with a relatively omnidirectional wind rose. It would be relatively simple at this scale to make the required allowances for surface roughness.

There are plans for NOABL's operating system to be transferred to a microcomputer which, with a transputer to improve its speed of operation, should widen the scope of NOABL and reduce computing costs.

Correction Of Wind Speed Models At Non Hilltop Sites Within 4Km Of The Coast

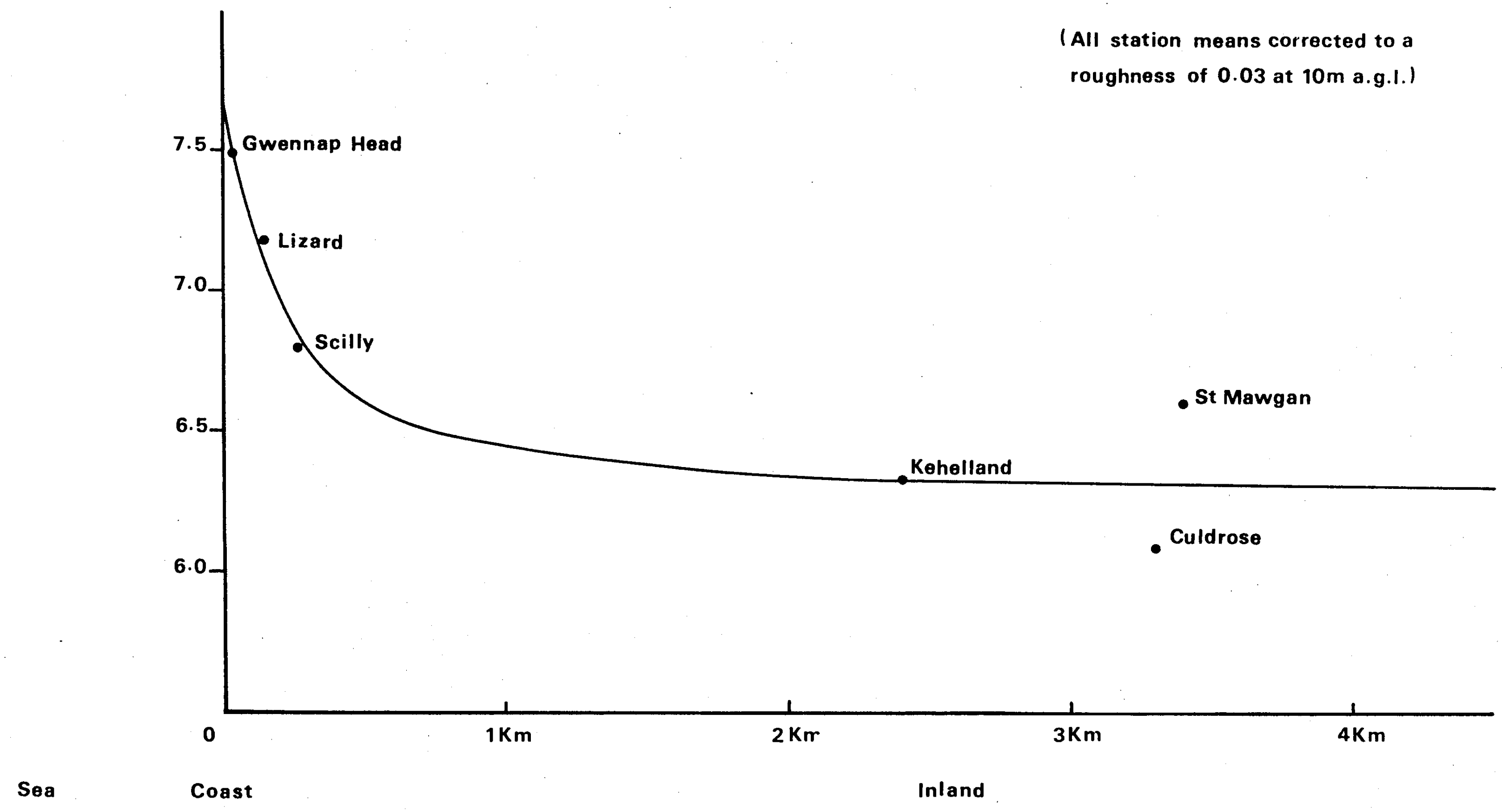


Figure 2j

The Testing Of A Combination Of Moore and Caton's Method Against The Field Data

The upper air wind data from Bennett, Hamilton and Moore was extrapolated downwards to 10m above surface level by using an exponent of 0.081. This exponent was derived from the field experiments with 10m, 20m, 30m and 52m towers and the Tala kite ascents. These results were corrected for the effect of ground elevation at the rate of 7% per 100m taking 70m as the datum. However, where an isolated hill or ridge rises directly out of a coastal plain then sea level is taken as the datum. The new, spot, wind speed values were converted into an isovent map by the Gino program and the map values are compared with field measurements of wind speeds in column A of table 2.11.

These generally showed an overestimation of 4% so all the results were reduced by this percentage and are shown in column B

Table 2.11 Combined Method:Reconciliation Before And After Calibration

Station	Column A Original Error %	Column B Final Error %
St Mawgan	+ 19.8%	Nil
Kehelland	+ 26.2	+ 2.1
Goonhilly	+ 30.02	+ 2.9
Treculliacks	+ 11.3	+ 6.7
Crowan	+ 1.04	Nil
Carland Cross	+ 1.03	1%
Lizard	+ 4.4	Nil
Gwennap Head	+ 2.2	Nil
Culdrose	+ 27.0	Nil
Trelow	- 9.1	Nil
Condolden	+ 3.8	+ 5.1
Tresparrett	- 0.5	Nil
St Agnes Beacon	- 25.7	Nil
Carn Brea	- 17.1	Nil
Carn Bean	+ 1.4	- 2.6
Watch Croft	- 0.36	Nil
Tregonning	- 16.4	Nil
West Penrice	- 5.0	+ 3.7
Melbur	- 0.5	Nil
Blackpool	- 1.0	+ 2.6
Park St Neot	+ 3.0	- 7.3

(Nil = less than 1% error. - = Method underpredicts field results. + = Method overpredicts field results

From the data it appears that:

1. This method generally overestimates the annual mean wind speeds by 4%. The error probably arises from either poor definition of the knee in the wind shear profile gradient, or because the Tala kite readings could not be made at sufficient altitude.

2. There is good correlation at the line of the coast, but this method overestimates wind speeds in the coastal littoral. This is to be expected from the mechanics of the method itself. Imagine winds with vectors which carry them from over the sea to over the land. As the change in roughness and elevation is encountered at the coast, it is felt first by winds nearest the surface and there is some delay until the slowing down of these winds is convected to the upper air levels by which time the air mass has travelled some way inland. As this method is based on the upper air winds, not those at the surface, this delayed retardation means that the wind speeds on the coastal plateaux, which are derived by an exponent drawn down from the upper air winds, overestimate surface wind speeds and need to be corrected for this effect. This is particularly marked on the Lizard. Here the land is too narrow to seriously retard the upper air and Moore and Caton's method overestimates mean annual wind speeds at ten metres above ground level. Correction coefficients were derived from a series of coastal anemometer stations. (See figure 2i)

3. The method underpredicts the speed up from steep hillsides. Correction coefficients were derived from the field data to amend annual mean wind speeds for these effects. Williams (1984)

When these three factors have been taken into account, errors are reduced to those shown in column B. Their standard deviation is 2.34% and the range of error is +/- 7.3%. These results are quite satisfactory for the purpose of this survey and are marginally better than the results obtained by NOABL. Another advantage of this method is the fact that it is quick and cheap to carry out. The isovents can easily be developed by hand from the spot heights at the small scale of the upper air wind speed map and can be enlarged to 1:50,000 with a pantograph using an underlying Ordnance Survey relief map. This avoids the expense of using a computer to run NOABL.

Final Choice of Mathematical Model To Predict Wind Speeds

Both NOABL and the amended method of Moore and Caton gave reasonable results. A combination of the two methods was used to derive wind speeds for the 1511 sites. Moore and Caton was used on the inland massifs and isolated hills as well as at the coast itself. NOABL was relied upon on the coastal benchlands. In both cases hill speed up factors had to be applied for terrain features too small to be "seen" by NOABL or the low resolution of the upper air data. The experimentally derived shear exponent was used to find hub height wind speeds. This work gave the following results:

2.5 Wind Survey: Results

Table 2.12. Sites As A Function Of Mean Annual Wind Speed At 25m Above Ground Level.

Wind Speed	Number of Sites.
Below 6.5m/s	1
6.50 - 6.75	178
6.76 - 7.00	249
7.01 - 7.25	107
7.26 - 7.50	246
7.51 - 7.75	189
7.76 - 8.00	230
8.01 - 8.25	102
8.26 - 8.50	90
8.51 - 8.75	63
8.75 - 9.00	36
>9.00 m/s	20

The average wind speed at hub height is 7.52m/s. The average hub height wind speed for the best 300 sites is 8.45m/s.

2.6 Wind Survey: Conclusion

Cornwall has a better wind resource than any yet developed in Europe and the top 20% of sites have better mean annual wind speeds than those in the wind districts of California.

Wind Survey References

BENNETT, M., HAMILTON, P.M. & MOORE, D.J. (1983)
"Estimation of low-level winds from upper-air data." IEE Proceedings, Vol 130, Pt.A, pp 517-525. No.9, December.

BERKHUIZEN, J.C., VAN DEN DOEL, J.C., SLOB, A.F.L, & DE VRIES, E.T. (1986)
"Estimation of the wind energy potential in the Netherlands taking into account environmental aspects." pp 563-567, European Wind Energy Conference. Rome, October.

BROOKS, E.M. (1983)
"Vertical profiles of wind speed at Medicine Bow." Wyoming, Department of Atmospheric Science, University of Wyoming.

CATON, P.G.F, (1976)
"Maps of hourly mean wind speed over the United Kingdom 1965 - 1973." Climatological Memorandum 79. Meteorological Office, United Kingdom.

CATON, P.G.F. (1976)
"Standardised maps of hourly mean wind speed over the United Kingdom and some implications regarding wind speed profiles." CUP.

DAVENPORT, A.G. (1960)
"The spectrum of horizontal gustiness near the ground in high winds." University of Bristol.

DEAVES, D.M. (1976)
"Wind over hills: A numerical approach." Journal of Industrial Aerodynamics Vol 1, pp 371-391.

DELAUNEY, D. (1986)
"Wind energy assessment of the Brittany region." Centre Scientifique et Technique Du Batiment. European Wind Energy Conference, pp 333-337. October.

DURST, C.S. (1960)
"Wind speed over short periods of time." The Meteorological Magazine. Vol 89 No. 1056, pp 181-186.

ENDLICH, R.M. & LEE, J.D. (1983)
"An improved diagnostic model for estimating wind energy." SRI International, SRI Project 4292, Prepared for Pacific Northwest Laboratory, Richland, Washington. March.

FRENKIEL, J. (1963)
"Wind profiles over hills in relation to wind power utilization." Israel Institute of Technology. Quarterly Journal, Royal Meteorlogical Society, Vol 89, pp281-283.

FRENKIEL, J. (1961)
"Wind flow over hills in relation to wind power utilization." Pub. Procs. UN Conference on New Sources of Energy, pp 85-111. Rome.

FROST, W. & NOWAK, D. (1977)
"Technology development for assessment of small-scale terrain effects on available wind energy." Pub. US Department of Energy, 3rd Wind Energy Workshop, Washington DC.

FROST, W. (1976)
"Analysis of wind turbine rotor responses to one-dimensional turbulence." Pub. University of Tennesse Space Institute. Contract Report NA58 32118.

HALLIDAY, J.A. & LIPMAN, N.H.
"Wind speed statistics of fourteen widely dispersed U.K. meteorological stations." Rutherford Appleton Laboratory, Department of Engineering, University of Reading.

HARRIS, R.I.
"The nature of the wind." Electrical Research Association.

HOLTSLAG, A.A.M, (1984)
"Estimates of diabatic wind speed profiles from near-surface weather observations." Royal Netherlands Meteorologial Institute, De Bilt, pub. Boundary Layer Meteorology, Vol 29, pp 225 -250.

JACKSON, P.S. & HUNT, J.C.R, (1979)
"Turbulent wind flow over a low hill." Dept. of Applied Mathematics & Theoretical Physics, University of Cambridge, pub. Quarterly Journal, Royal Meteorlogical Society. Vol 101.

MORGAN, W.R. (1936)
"Relation between ground contours, atmospheric turbulence, wind speed and direction." Pub. HMSO.

NEWTON, K., & BIRCH, S. (1984)
"Estimation of the UK wind energy resource using computer modelling techniques and map data : A pilot study." ETSU R 17.

PALUTIKOF, J.P., HALLIDAY, J.A., DAVIS, T.D., BASS, J.H., HOLT, T., WATKINS, C.P., & KELLY, P.M., (1987)
"Development of a site wind-regime prediction methodology for Britain: work in progress." Climatic Research Unit, University of East Anglia. Energy Research Group, Rutherford Appleton Laboratory pp 271 -278. BWEA Conf. Procs, Edinburgh, April.

TAYLOR, P.A. & GENT, P.R. (1974)
"A model of atmospheric boundary-layer flow above an isolated two-dimensional hill : An example of flow above gentle topography." Pub. Boundary-Layer Meterology, 7, 349-362.

THEUNERT, S. (1984)
"Wind energy siting in coastal regions using numerical mesoscale modelling." Institut fur Meteorologie und Klimatologie, Universitat Hannover. pp 23-27. Procs. of European Wind Energy Conference, Hamburg, October.

TROEN, I., DE BAAS, A. (1986)
"A spectral diagnostic model for wind flow simulation in complex terrain." Procs. European Wind Energy Conference, pp 243-249. Rome Oct.

VERMEULEN, P.E.J., HOOGEVEEN, H., & LEENE, J.A. (1984)
"A handbook for wind energy production estimates in the Netherlands." Department of Fluid Dynamics MT-TNO, Centre for Energy Conservation, October.

WHEELER, R.E. & BAILEY, B.H.
"An extrapolation technique to estimate the climatological mean wind speed at a candidate site." Atmospheric Science Research Center State University of New York at Albany.

WIERINGA, J. (1986)
"Roughness-dependent geographical interpolation of surface windspeed averages." Quarterly Journal Of The Royal Meteorological Society. Vol 112, pp 867-889.

3. WIND TURBINE NOISE

Abstract

The pattern of rural settlement in Cornwall means that wind turbines have to be sited only a few hundred metres from habitations, with the result that noise is the dominating environmental issue. The problem has seven elements:

1. Noise Output From The Wind Turbines

The sound power level predictions from the five existing noise models did not agree with the field results. A new, interim prediction method was derived which showed good agreement. Turbine noise output varies pro rata with turbine size, or power, and is conditioned by blade tipspeed. Sound power levels for state-of-the-art machines range from 90dB(A) at 15m diameter to 112dB(A) at 91m diameter.

2. Sound Attenuation With Distance From The Wind Turbine

Here again the models were not adequate. The field observations for eight machines indicated the following rates of attenuation:

For up to about two diameters from the turbine: 3dB per doubling in distance.

From 2 to 10 diameters from the machine: 6dB per doubling in distance, plus the effect of atmospheric absorption at a rate of 2dB per 1000m.

Beyond 10 diameters there is much less certainty. For this report it was assumed that state-of-the-art machines continued to have the attenuation rate of 6dB per doubling in distance, plus an allowance for atmospheric absorption. In this zone the following factors had most influence:

Ground absorption: A better model is needed than those which were used in this report.

Wind profile gradients: These determined that the down wind case dominated the consideration of noise from wind turbines.

Barrier attenuation: This could not be applied to the general case and was omitted from this survey.

Topographical effects: These are very important in reducing, or increasing the rate of attenuation. These effects were not applicable to the general case, but an accurate model is required to check each turbine installation where development is proposed.

Atmospheric conditions and inversions: The latter did not occur with sufficient frequency to present a problem.

The field results already available appear to indicate that a machine <u>wholly designed to be quiet</u> has, quite fortuitously, exploited a mechanism which increases the rate of attenuation beyond 10 diameters to over 12dB per doubling in distance. More work and data is needed on this issue.

It was found that the threshold of aural perception, or detection distance, for wind turbine noise varied disproportionately with turbine size. Small/medium size machines had smaller specific noise footprint areas per installed kW than large machines. Detection distances varied from well under 300m for small machines to well over 3km for large machines and by extrapolation, detection levels were found to be up to about 10 dB(A) below the background levels. Machines with a frequency spectrum mirroring the ambient frequency spectrum reduced this figure to under 6 dB(A).

In Cornwall, over 90% of prospective sites were on hilltops. For over 2000 hours per annum state-of-the-art wind turbines will be close to their maximum acoustic output during which time neighbouring hillside and downwind valley properties experience negligible wind induced noise. As such, the quickly modulating relief typical of Western Britain represents a new and particularly severe acoustic environment in which to develop wind energy.

3. Ambient Noise Levels

Over forty measurements on thirteen sites assessed background noise levels at typical hillside or valley bottom habitations as a function of the hilltop, hub height, wind speeds. Daytime ambient levels for the wind speeds which occur for over half the year varied from 25dB(A) to 27dB(A), but these dropped to 21dB(A) to 23dB(A) in the evenings. It is in the evenings when habitations have their highest rate of occupancy and maximum annoyance can occur. These measured levels are much lower than the assumed background levels in noise codes used in Denmark, Holland and California.

4. The Effect Of More Than One Machine

If ten or more machines could be located in the same position as the original machine, then noise levels would rise by 10dB(A). In practice, some of these machines will be further away from the observer, so the sum of noise is likely to be below ten dB(A). Comprehensive field results are needed to confirm the sum of noise model when applied to wind turbines.

5. District Council Noise Standards

West Country District Councils apply a common condition to new developments in the countryside. This says that there should be no increase in ambient noise levels at the legally owned boundary of the property from which the noise emanates. For a typical hilltop site where the wind turbine(s) may occupy an "island" plot of only a few square metres of land this standard will be impossible to achieve. However, in most cases the land between the turbine and the nearest dwelling has a very low occupancy level so it is proposed to use a noise level which the public is likely to accept and to apply this standard to the boundary of the nearest habitation, not to the boundary of the turbine site.

6. Public Reaction To Turbine Noise

62 properties around six UK turbines were visited and the public reaction assessed. Noise was the major environmental concern and caused more annoyance than any visual effect. The people interviewed said that the noise was acceptable at levels which were extrapolated to only about 2dB above the detection limit. Above this level there was vigorous opposition to turbine installations. Almost all people found it unacceptable if they could hear the turbines indoors. The clear consensus was that turbines could be seen, but not heard.

7. Action Levels Under Control Of Pollution Act 1974, And Land Compensation Act 1972

Environmental Health Departments of District Councils in Cornwall take abatement action for an exceedance of 10 dB(A) above ambient in the curtilage of a dwelling. Four planning consents in the west of England have been on a temporary basis to ensure operators comply with these and other conditions. One turbine, which raised noise levels at a complainant's dwelling in excess of 10dB(A) above ambient, has been stopped from operating at night and has not been granted a permanent planning permission at the end of its first temporary consent period. The regional publicity given to wind turbine noise has sensitised opinion in the West Country to this potential problem.

A statutory undertaking is liable to pay compensation to householders for noise nuisance. In previous cases arising from traffic noise emanating 730m from a dwelling, the householders were awarded compensation at an average of 7.5% of their property's value. A utility owned, state-of-the-art machine surrounded by about 20 detached, rural properties each valued at over £125,000 could have to pay compensation which would make turbine installations uneconomic.

The author's machine is the quietest yet built in relation to its size. Further engineering studies indicate that it should be possible to reduce the noise levels at typical observer distances by 13dB(A) below the state-of-the-art noise level.

This would raise ex-factory turbine prices by about 5%. A 13dB(A) sound level decrement for quiet machines and a 5% increase in price are the assumptions used in the remainder of this report.

A worked example is presented which compares the noise levels at typical habitation separation distances from two hypothetical windfarms each of about 4MW capacity. One windfarm operator chose state-of-the-art machines of 33m diameter. This had an exceedance of about 27dB(A) above ambient. The other operator specified smaller machines designed to be quiet. These were inaudible by day and, depending on the shape of the frequency spectrum, would have been inaudible or barely audible in the downwind direction in the evenings.

Therefore, the noise problem does appear to be soluble providing that quiet machines are developed which reach their target noise levels, and providing that wind farm operators specify machines of a size which will not cause noise nuisance.

As a result, the following standard is proposed for Cornwall and is used in the subsequent assessment of the county's resource.

WIND TURBINE INSTALLATIONS SHOULD BE PLANNED ON THE BASIS OF BEING INAUDIBLE WITHIN THE CURTILAGE OF ANY HABITATION OR HEAVILY FREQUENTED AREA DURING NORMAL OPERATING AND ATMOSPHERIC CONDITIONS.

<u>Infrasound</u> This does not appear to create a problem.

3.1 Wind Turbine Noise: The Problem

A preliminary review of the factors which affect the wind resource in Cornwall identified noise as the most serious restraint and the one most likely to lead to complaint. Williams (1987). The problem arises from the fact that the pattern of rural settlement in Cornwall (and much of England and Wales) dictates that it is not possible to find sites for wind turbines more than a few hundred metres from habitations. The situation is made worse by the very low background noise levels recorded in the rural parts of Cornwall.

3.2 Wind Turbine Noise: Aim

The aim was to determine acceptable separation distances from habitations for different types and size of wind turbine.

3.3 Wind Turbine Noise: Method

The method consisted of first, splitting the problem down into seven elements:

1 The level of noise output from the wind turbine.

2 The degree to which turbine noise is attenuated with distance from the machine.

3 The background noise levels at the places where people will be most affected by the turbines.

4 The effect of more than one machine.

5 Noise standards set by District Council planning departments.

6 The noise level at surrounding habitations below which plans for subsequent installations in the area will not lead to significant public opposition. This is a prime consideration in developing a wind district which may involve multiple planning applications being made over a period of years.

7 Should a problem arise after installation, the noise level at which complaints are likely to lead to abatement action. This remedy can be obtained by either the Environmental Health Departments of District Councils, or householders, seeking a noise enforcement order in the Magistrates' Courts under the provisions of the Control of Pollution Act, 1974. If the noise is created by machines owned by a statutory undertaking, what are the levels and associated rates of compensation that may be claimed successfully under the provisions of the Land Compensation Act, 1973 ?

Then, each of these seven elements was examined under the headings of:

- Problem
- Aim
- Method
- Work Done
- Results.

Finally, a composite result was derived from these seven elements of the problem and a recommended noise standard was proposed which then became the basis for this study.

3.4 Wind Turbine Noise: Work Done

3.4.1 Noise Output From Wind Turbines

A number of noise prediction methods were available. These were reviewed and then tested against the field data in order to select the most reliable model:

Noise "Generators" Used In Analysis.	Viterna Nasa Lewis 1980	Keast & Potter 1980	Hubbard Shepherd Grosveld 1981	Glegg ISVR S'ton 1984	Grosveld Bionetics Corp. 1985
Rotor					
Inflow Turbulence	Yes	Yes and	Yes and	Yes	Yes
Turbulent Bdry Layer/Trailing Edge	No	Yes but only via blade area and speed.	Yes but only via blade area and speed	Yes	Yes
Trailing Edge Thickness	No	No	No	No	Yes
Stalled Condition	No	No	No	Yes	No
Shear	Yes	No	No	Yes	No
Tower Shadow	Yes	No	No	No	No
Tower Reflection	No	No	No	Yes	No
Ground Reflection	Yes	No	No	Yes	No
Observer Direction and distance.	Yes	No	Yes	Yes	Yes
Tip Fairing	No	No	No	Yes	No
Tip/Blade Slot	No	No	No	No	No
Far field Prediction	No	No	No	No	Yes

Noise "Generators" Used In Analysis	Viterna Nasa Lewis 1980	Keast & Potter 1980	Hubbard Shepherd Grosveld 1981	Glegg ISVR S'ton 1984	Grosveld Bionetics Corp. 1985
Other Components					
Generator Noise	No	No	No	No	No
Gearbox Noise	No	No	No	No	No
Sound Radiation From The Tower	No	No	No	Yes	No
Results (f) Frequency	Yes	Yes by ref. to peak freq. and idealised shape.	No	Yes	Yes
Program written	Yes	No	No	Yes	No
and available	No	No	No	Yes	No

Testing The Validity Of The Noise Codes Against Field Measurements

Method Of Hubbard, Shepherd and Grosveld. College Of William and Mary, Newport News, Virginia.

Viterna's WT SOUND program could not be obtained. Hubbard's method was similar in principle to that of Keast and Potter, ie sound output is a function of turbine power, or swept area, and is conditioned by tipspeed. In the 1950's Hubbard had devised some charts for the prediction of noise made by the propellers of transport aircraft. These had been used successfully. For the preliminary paper on wind turbine noise (Williams, March 1987), Hubbard's expression was slightly modified to:

$$\text{Sound Pressure Level } dB(A) = 10 \log (K.V.A^{6}) - 20 \log (0.011x) + 20 \log (\sin Q/0.25a) - 4dB$$

Where log is to base 10 and
K = 5.1 x 10 Exp -7.
A = Total area of blades in sq. m.
V = Velocity of blade at 70% radius.
x = Observer distance in m.
Q = Angle in degrees of observer from axis of rotation.

This was tested against the reported data for eight machines. The results gave a mean error of 2.4%. However, when all 22 field data had been culled from the literature, the method showed large errors and had to be abandoned.

Glegg's Method. Institute Of Sound And Vibration, Southampton.

This was transcribed so that it could be used on an IBM compatible microcomputer. Twenty-five runs were conducted with different input data, but it was found that the results from the program:

a. Did not match the field data.
b. Did not account for the change in noise output as turbines got bigger. It forecast the same noise from geometrically identical rotors of 4m and 105m diameter.
c. It overpredicted both very high and very low frequencies. The author could not be traced and as a few elements of the program were not fully explained in the report we were unable to alter the source code. This method was also abandoned.

Grosveld's Method. Bionetics Corporation, then NASA Langley.

This was the most recent model. It was clearly presented and had the benefit of new findings in the NASA Langley quiet flow facility in defining 5.4 as the exponent for trailing edge thickness noise. There were comprehensive references. The author supplied us with the empirical coefficients which were needed as input to the three equations which make up total rotor noise:

Turbulent Inflow:

$$|p^2| = K_1(f) B \sin^2\phi \, \rho^2 c R w^2 U^4 / (r_0^2 c_0^2)$$

where P = Mean sound pressure level in far field in dB
K_1 = Empirical constants
B = Number of blades
ϕ = Angle between vector from source to receiver and its projection in the rotor plane in degrees.
ρ = Density of air kg/cu m
c = Blade chord in m
R = Rotor blade radius in m
w = Square root of mean square turbulence intensity
U = Freestream velocity m/s
r_0 = Distance between source and receiver in m
c_0 = Speed of sound (330m/s)

Turbulent Boundary Layer/Trailing Edge Interaction:

$$SPL_{1/3} = 10 \log \left\{ K_2 U^5 B D \frac{\delta s}{r_0^2} \left(\frac{S}{S_{max}}\right)^4 \times \left[\left(\frac{S}{S_{max}}\right)^{1.5} + 0.5\right]^{-4} \right\}$$

where K_2 = Empirical coefficient - 3.5.
D = Directivity
δ = Boundary layer thickness
s = airfoil span
S = Strouhal Number = frequency x boundary thickness/U

Trailing Edge Bluntness Vortex Shedding Noise

For conditions where trailing edge thickness/boundary layer thickness is: $\frac{t^*}{\delta} > 1.3$

Sound Pressure Level =

$$SPL_{1/3} = 10 \log \left[\frac{K_3(f) B U^6 t s \sin^2\theta \sin^2\psi}{(1 + M\cos\theta)^6 r_0^2} \right] \quad \text{and} \quad f_{max} = \frac{0.25U}{t + \delta/4}$$

For conditions where trailing edge thickness/boundary layer thickness is: $\frac{t^*}{\delta} < 1.3$

Sound Pressure Level =

$$SPL_{1/3} = 10 \log \left[\frac{K_4(f) B U^{5.3} t s \sin^2(\theta/2) \sin^2\psi}{(1 + M\cos\theta)^3 [1 + (M - M_0)\cos\theta]^2 r_0^2} \right] \quad \text{and} \quad f_{max} = 0.1U/t$$

where K_3 = A frequency dependent constant
K_4 = A frequency dependent constant
t = trailing edge thickness in metres
g = angle between source to receiver line in the vertical plane and its projection in the rotor plane
h = as g, but in horizontal plane
J = spanwise length of blade element
M = Mach number
Mc = Convection Mach number

To evaluate the expressions for trailing edge interaction and trailing edge bluntness, the blade is divided into four segments before summing their results and then adding the noise from the remaining expressions.

These formulae were programmed by Dr Nevitt of Windpower & Co to run on an IBM compatible PC. However, we were unable to replicate the author's results and could not match his or other field data, nor get agreement with the results from three other machines for which we had field measurements. Grosveld is now rewriting this program with the following changes:

a. new empirical constants
b. a different Strouhal number for the prediction of trailing edge bluntness vortex shedding
c. a different input to account for shear and turbulent intensity.

A revised version of the code was not expected until after the reporting date for this project.

Therefore, a new code had to be developed for the purpose of this survey.

Development Of A New Wind Turbine Noise Prediction Method

The steps were:
1. The literature was searched and turbine manufacturer's were asked for their turbine's field results of noise. From the references given at the end of this chapter 22 records were compiled of the noise output from wind turbines. Much of this information was badly reported and often had to be checked in several publications. The measuring methods and positions were not consistent, so they were reduced to a common basis in the following way:

Wind Speed and Power Output It is very difficult to get accurate field results when the hub height wind speed is above 10m/s because wind noise then seriously affects the accuracy of the noise meters. Most records were made at between 5m/s and 8m/s. Records made of the same machine at different wind speeds were used to reduce or interpolate the data to a common measuring condition of between 6m/s and 7m/s wind speed at hub height.

Position Of Measurements Relative To Wind Turbine Most observers recorded the noise downwind of the turbine. In two instances the measurement position was up to 60 degrees off the downwind axis. Where this occurred the mean shape of the noise polars around three other turbines, which were in good agreement with each other, were taken as the shape of the machine under investigation. This mean noise polar shape was then used to determine the noise level in the down wind position.

Distance From The Machine At Which Measurements Were Made. If measurements were made at more than three diameters from the machine these were rejected, those remaining were corrected to a distance equal to one blade length plus hub height from the machine. Ljunggren and Gustafsson (1984). The correction was made by assuming an attenuation rate of 3dB per doubling in distance for up to two diameters from the machine and 6 dB(A) per doubling in distance beyond that point.

Correction For Ground Reflection The majority of measurements listed in the literature had been made by placing the microphone in the middle of a flat, stiff board placed directly on the ground. Andersen and Jakobsen (1983). The others were taken at about 1.2m above ground level and these results were raised by 3dB to account for the increased acoustic reflections arising from the hard plate method.

The noise level from the author's machine was measured with Bruel and Kjaer equipment by the County Noise officer using the procedure outlined by Andersen and Jakobsen (1983). Noise levels in a variety of wind conditions were also made by Windpower staff using a Dawes hand held meter.

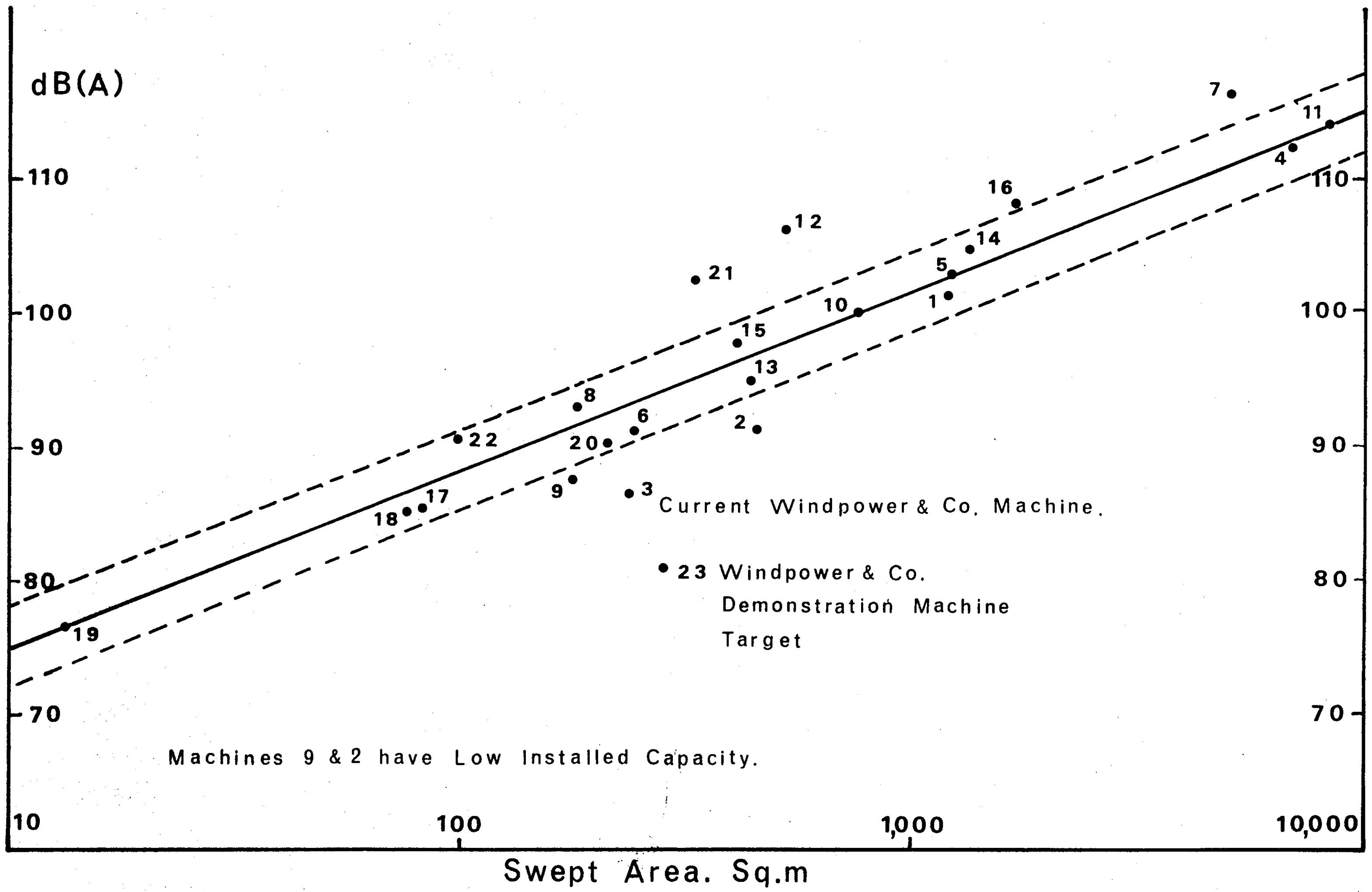
These results and those derived from the literature and from the manufacturers had now been corrected by the above procedure to have a common measuring position relative to the wind turbine and common operating conditions during the taking of measurements.

The turbine's sound power level was found by the following formula:

$$\mathrm{Lwa} = \mathrm{Lpa} + 10 \log_{10} 4\pi\left(d_2 + h_2\right) - 6dB\ (A)$$

Where Lwa = sound power level in dB(A)
Lpa = the field measurement of sound pressure level in dB(A)
d = the horizontal distance from the foot of the tower to the measuring position in m.
h = the distance from ground level to hub height in m.

The results are graphed in figure 3a. They show a strong correlation between machine swept area (or ipso facto machine installed power) and sound power level. The author's machine is the quietest for its size and on checking the literature records it appeared also to be the only machine which had the benefit of substantial noise attenuation equipment in the nacelle. Now the noise prediction codes had all ignored the contribution to total noise made by the generator and gearbox, and the result from the author's machine suggested that their contribution is significant. Therefore, standard gearbox and generator sound power levels were obtained from VDI 2159, 1985 and from Fasold et al 1984. See figures 3b to 3d. The noise contribution from the gearbox and generator as described in these graphs was deducted from the sound power level of the 22 machines to give the rotor only noise level. The new trend line of rotor sound power level as a function of swept area had a marginally flatter trend line than that the whole machine of figure 3a.



Wind Turbine Sound Power Level - Field Results.

Figure 3a

Sound Power Level (f) Gearbox Capacity

Source: VDL 2159 (1985)

Figure 3b

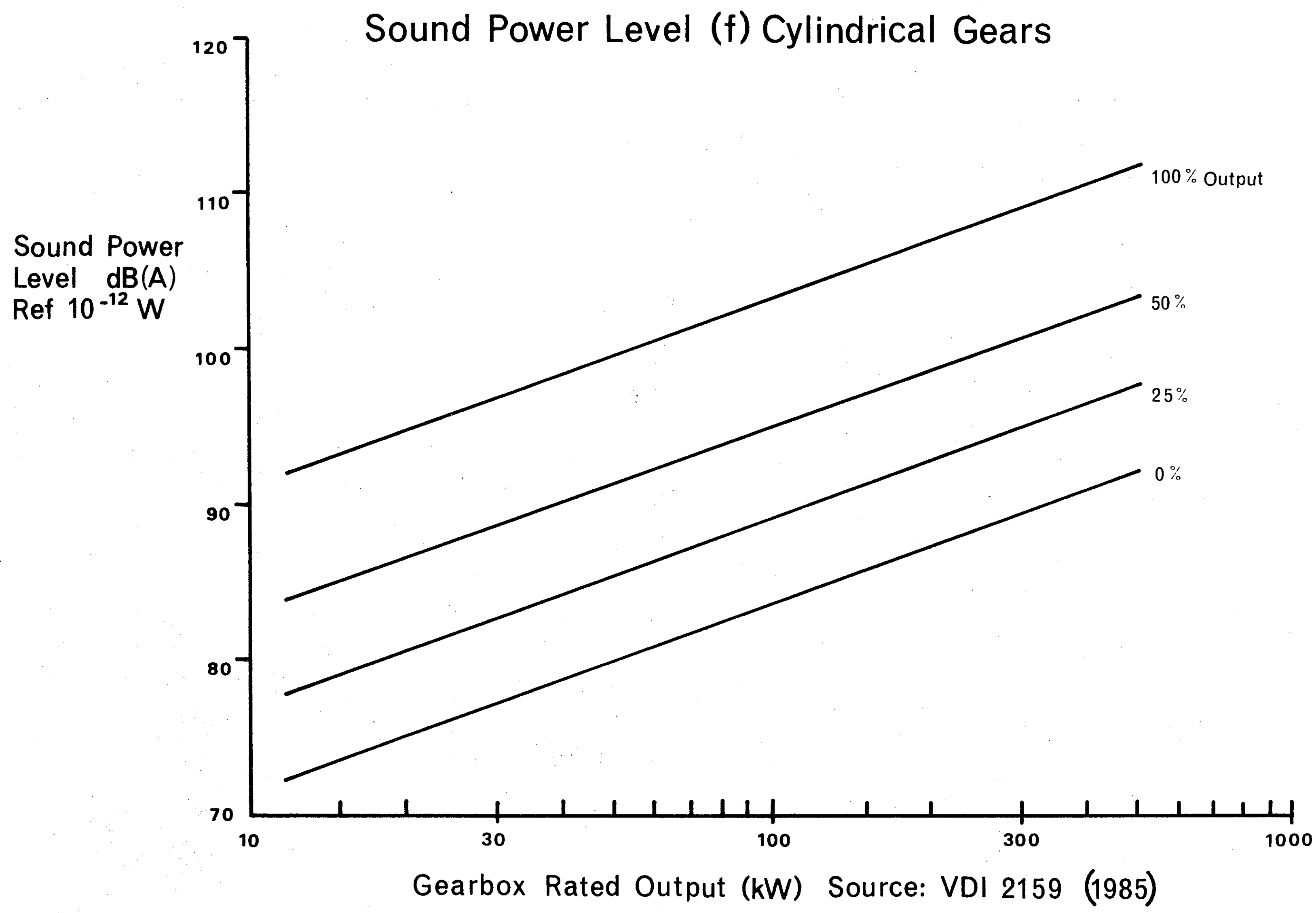

Sound Power Level (f) Cylindrical Gears
Sound Power
Level dB(A)
Ref 10^{-12} W
120
110
100
90
80
70
100 % Output
50 %
25 %
0 %
10
30
100
300
1000
Gearbox Rated Output (kW) Source: VDI 2159 (1985)

Figure 3c

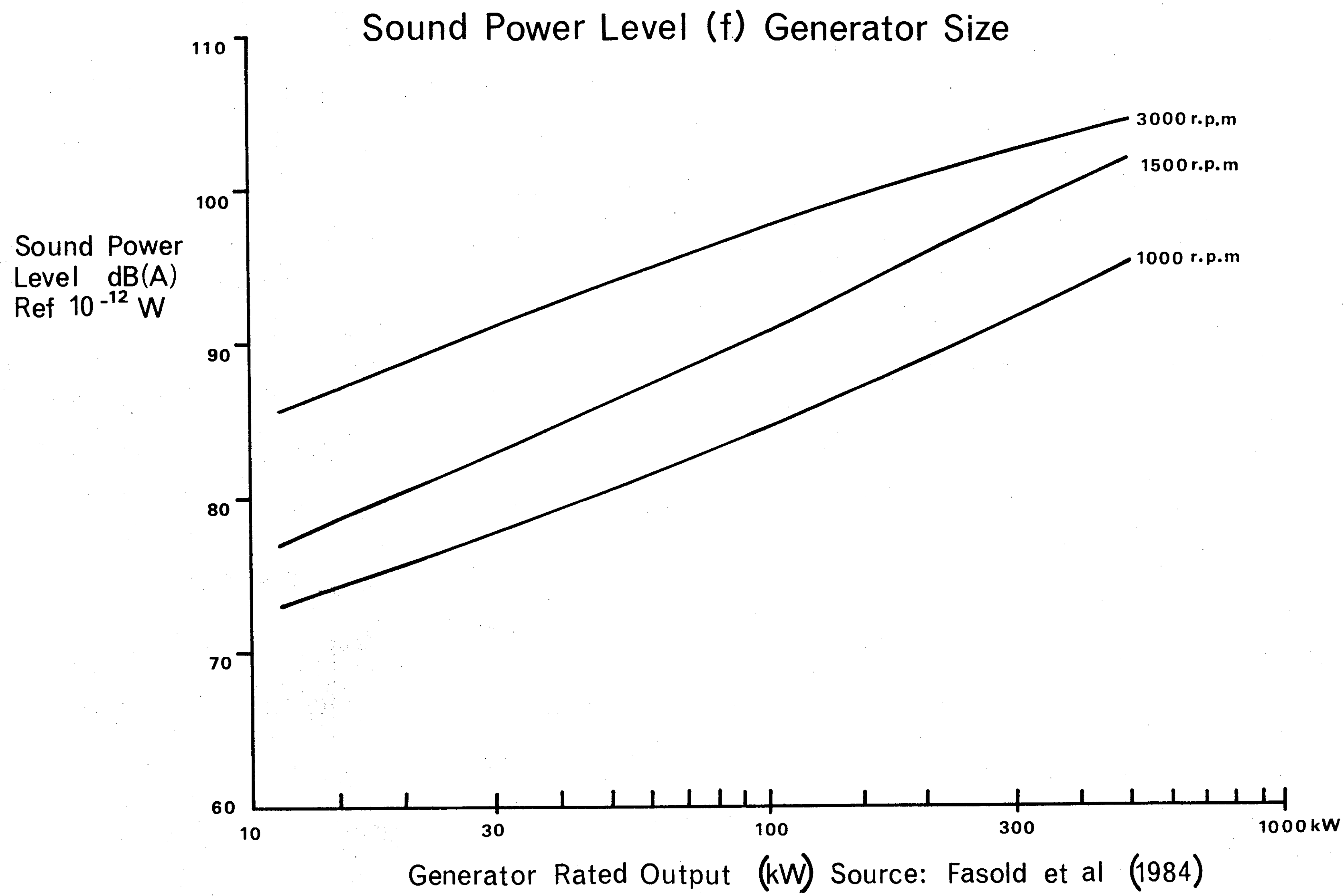

Sound Power Level (f) Generator Size
Sound Power
Level dB(A)
Ref 10^-12 W
110
100
90
80
70
60
3000 r.p.m
1500 r.p.m
1000 r.p.m
10
30
100
300
1000 kW
Generator Rated Output (kW) Source: Fasold et al (1984)

Figure 3d

Rotor Sound Power Level

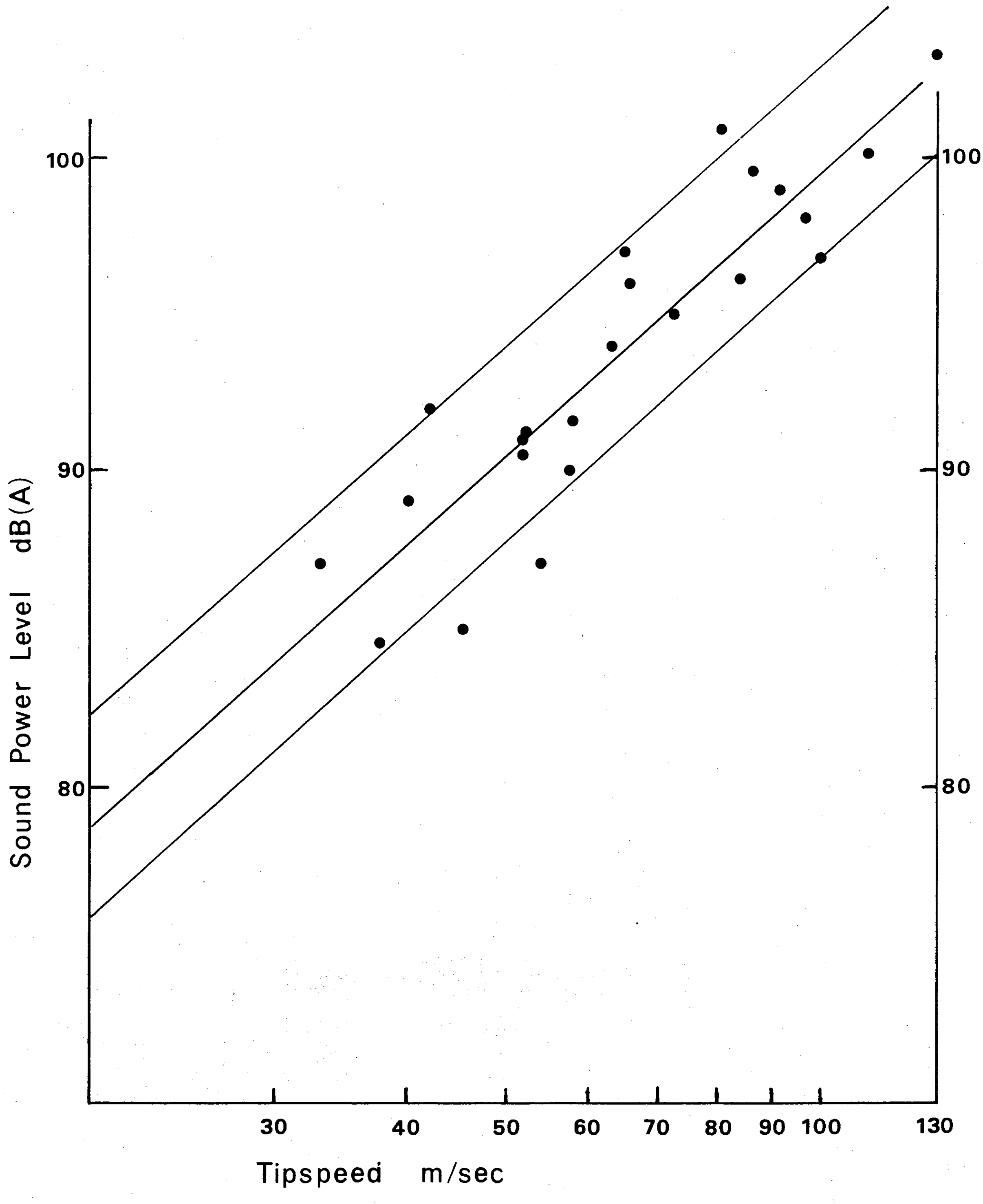


Figure 3e

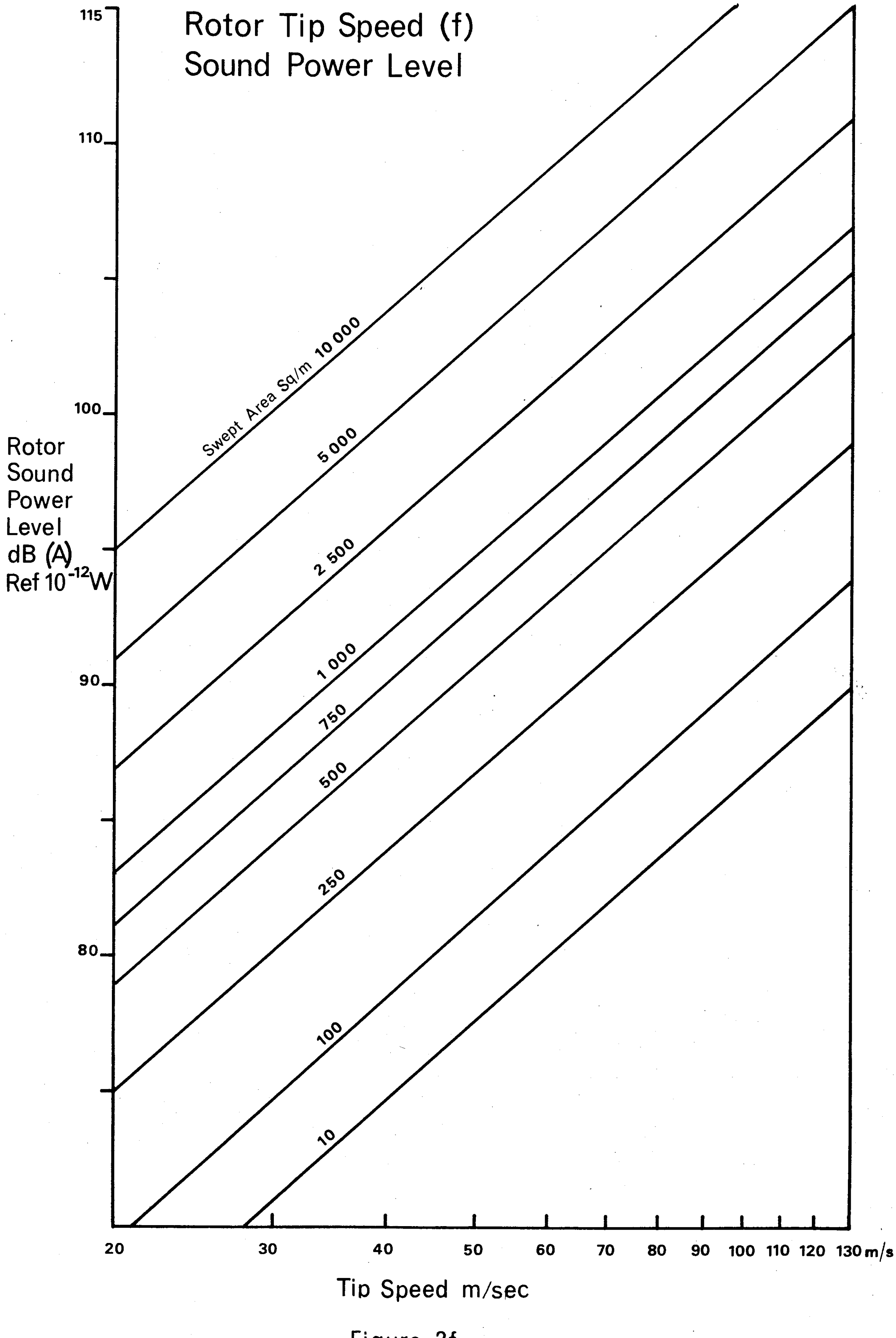

Rotor Tip Speed (f)
Sound Power Level
115
110
100
90
80
Rotor Sound Power Level dB (A) Ref 10^{-12}W
Swept Area Sq/m 10 000
5 000
2 500
1 000
750
500
250
100
10
20
30
40
50
60
70
80
90
100
110
120
130 m/s
Tip Speed m/sec

Figure 3f

The rotor trend line was used to normalise the rotor sound power levels to a common swept area of 500 square metres and the results replotted with tipspeed along the x axis. The result is shown in figure 3e where all the measurements are plus or minus 4 db from the trend line except for the author's machine which is 5dB below the trend line. Now as VDI 2159 and Fasold show that the rotor noise only accounts for about one third of the total noise from the turbine this +/- 4dB degrees of error will be diluted to less than +/- 3 dB when it is summed with the gearbox and generator sound power levels both of which are available as measured data from their manufacturers. Therefore, the trend line of the rotor noise, added to the manufacturer's data for generator and gearbox noise, together with an allowance for any sound attenuation measures in the nacelle, should give a sound power level prediction method with an error of less than +/- 3dB. This is better than any of the models reviewed above and is quite adequate for the purposes of this survey. Therefore, the tipspeed trend line for a rotor area of 500 square metres was expanded to other swept areas as shown on graph 3f and this is used in the following way in the new prediction method:

1. Find rotor sound power level (LwaR) from figure 3f in dB(A).
2. Find gearbox sound power level (LwaB) from figure 3b in dB(A) and deduct the value of any sound attenuation measures.
3. Find the generator sound power level (LwaG) from figure 3d and deduct the value of any sound attenuation measures.

The predicted Sound Power Level of the turbine (LwaT) is:

$$\text{LwaT} = 10\log_{10}\left(\frac{\text{LwaR}}{10}\right) + 10\log_{10}\left(\frac{\text{LwaB}}{10}\right) + 10\log_{10}\left(\frac{\text{LwaG}}{10}\right)\ dB\ (A)$$

To test the method it was used to predict the sound power levels of the 22 machines mentioned above. The results are tabulated below:

Table 3.1 Reconciliation Between New Method Of Turbine Noise Prediction And Field Results

	Machine	Dia. (m)	Installed Capacity (kW)	Error (%) + = Model Overpredicts - = Model Underpredicts
1	MOD 0	38.1	100	+0.09
2	Gedser	24.0	200	+0.4
3	Windpower 1.	17.5	140	+0.1
4	MOD 2	91.4	2.5MW	+0.6
5	MOD OA	38.1	200	Nil
6	US Windpower	17.6	50	+1.7
7	Hamilton Standard WTS 4	78.05	4MW	+0.5
8	Vestas	15.0	55	-1.1
9	Vestas (Low rpm)	15.0	55	-2.3
10	Petten	30.0	300	+1.9
11	Growian	100.0	3MW	+1.5
12	WEG MS2	25.0	200	+1.7
13	Danwin	23.2	180	+0.2
14	D.W.T.	40.0	750	+1.0
15	HMZ	22.5	200	-0.2
16	NEWECS 45	45.0	1MW	-0.24
17	Grumman 33	10.1	8	-3.2
18	United Tech.	9.6	8	-0.82
19	Dunlite	4.1	2	-0.65
20	Bouma	16.0	55	-0.44
21	WEG MS1	20.0	250	-0.05
22	Paques	11.0	17.5	-7.1

This method gives sufficiently accurate results for this study. It confirms the strong link between turbine size (or power) and sound power level. It shows that the author's machine is the quietest yet built for its size.

More work is needed to determine the reasons why different rotors appear to vary so much in their noise output so that the best elements of the mathematical models reviewed above can be recast into an accurate predictive tool. In particular, designers need to know the contribution of different tip and root shapes, the contribution of different levels of site inflow turbulence, the exact degree of rotor fairness which is required to avoid noise generation, the contribution from a cut off trailing edge for the NACA aerofoils and further confirmation that the square trailing edge of the NASA LS1 series is not a noise generator. (The author's machine has an LSI aerofoil with square trailing edges).

3.4.2 Wind Turbine Noise: Attenuation With Distance From The Source(Ae)

A Review Of The Main Mechanisms

For hemispherical spreading in an homogeneous, loss free atmosphere and over a loss free, flat, ground, the sound pressure level drops off at 6dB for each doubling of distance, or 20dB for each factor of ten in distance. Therefore, if we have the sound pressure level (SPL1) for a distance (d1 in metres) from a point source then:

$$SPL_2 = SPL_1 - 20\log\left(\frac{d_2}{d_1}\right) - A_e \; dB$$

Where SPL_2 = the sound pressure level in dB at the position of interest at a distance d2 (in metres)

A_e = accounts for any excess attenuation arising from conditions which depart from the base case.

If the source is a rectangular area, then successive rates of attenuation will be:

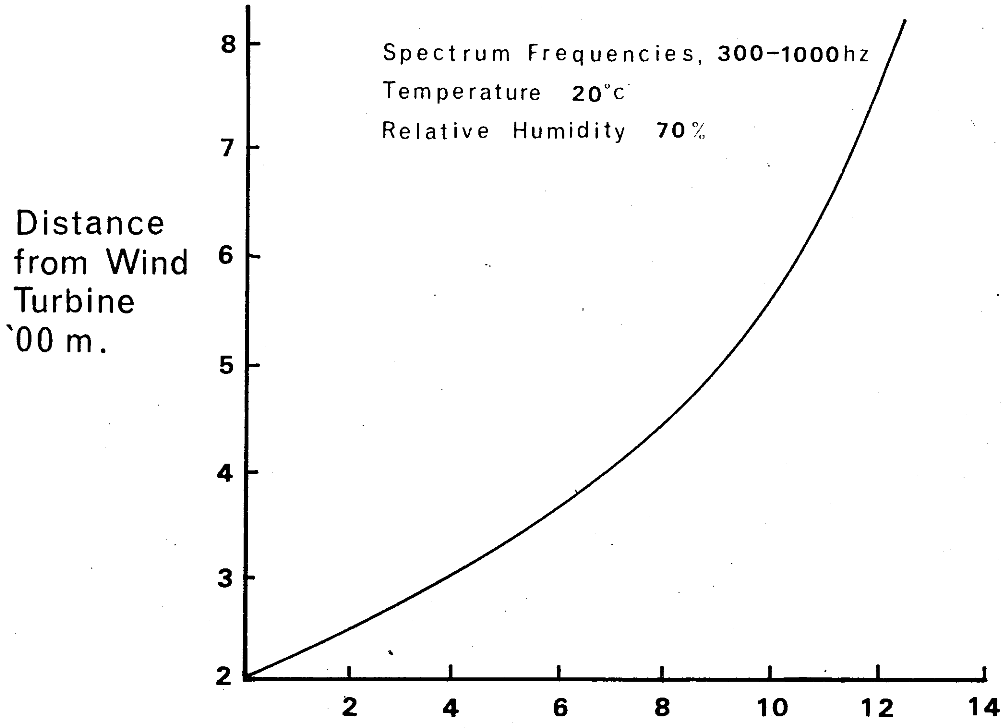
1. Nil attenuation for a distance of: (the shortest side of the noise source/3.14) from the source, followed by:
2. Attenuation at a rate of 3dB per doubling in distance until a position is reached where the noise source appears to act as if it were a point, not an area.
3. Attenuation continues at a rate of 6dB per doubling in distance from the source.

Rathe (1969)

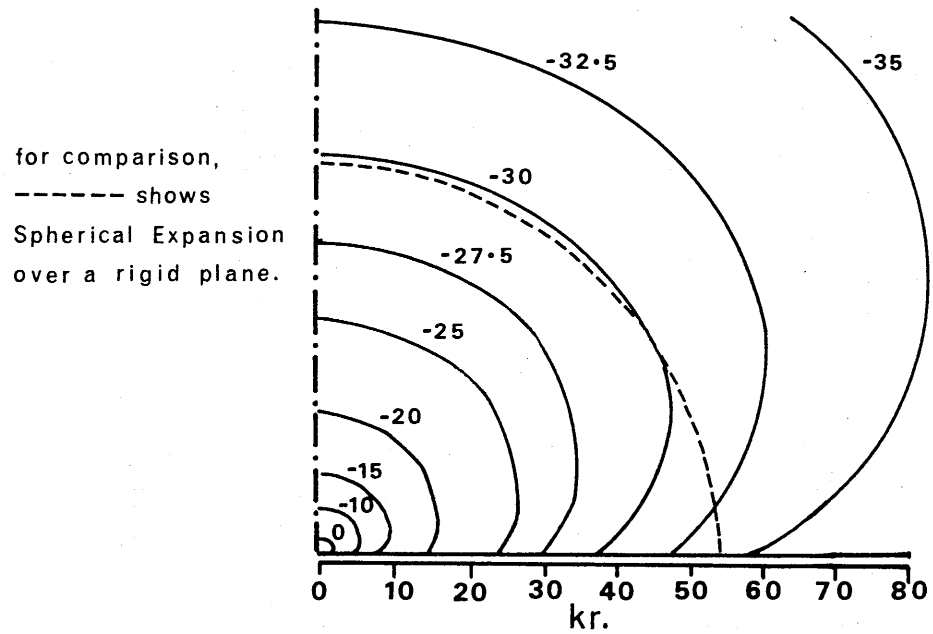
Upon this basic attenuation pattern the following factors (Ae) will then be imposed:

Air Absorption (Af)

For air to ground propagation, at a geometric mean frequency of 500hz in 90% humidity and between 0 and 20 degrees C allow 2dB per 1000m. Beranek (1971). Figure 3g shows a combination of hemisherical spreading from a point source combined with air absorption.



Noise Attenuation (f) Distance. (Spherical Spreading + Atmospheric Absorption Only.)



Pressure distribution around a Point Source

Figure 3g

Ground Absorption (Ag)

Reflection of sound by a surface may affect the sound pressure level at an observer in two ways. The reflected wave will combine with the direct wave if the frequencies are in phase and result in higher than expected noise levels, or alternatively they will cancel each other out if they are in antiphase. Secondly, there will be a loss of acoustical energy by surface absorption. The latter can be neglected within about 2 to 3 diameters of the source, but for greater distances over thick grass it is forecast approximately from:

Ground attenuation = $(0.18 \log f - 0.31d)$ dB

Where f = frequency of sound in Hz,
d = path length in metres over grass.

For the frequency spectrum of WP1 (the author's machine) this would amount to 5.5dB per 100m if the source was at ground level, but will only be some fraction of this due to the elevation of the rotor. The effect of raised source height has been developed from Pao et al (1978) for aircraft. Neither approach matched the field results. A better model is needed.

A cross sectional view showing how ground impedance affects sound waves close to the surface (figure 3g) means that an observer elevated above the ground may well experience higher sound levels. This has implications for habitations which would experience higher sound levels at the bedroom windows and where high walls may reflect sound waves down into the curtilage of a dwelling.

Wind Profile Gradients (Ah)

Figure 3h shows how wind shear reduces the upwind and extends the downwind sound footprint from a turbine.

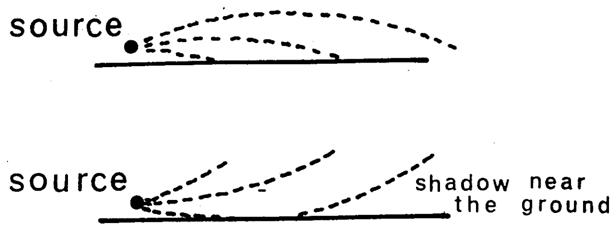
Barrier Attenuation (Ai)

Hedgerow trees, shelter belts, woodlands, hedges and buildings will have site specific effects on attenuation rates, but cannot be quantified for the general case.

Noise Refraction

a.

b.



a. Refraction Downward — Inversion, or Downwind Propagation.

b. Refraction Upwards — Lapse, or Upwind Propagation.

Figure 3h

Atmospheric Attenuation Factors (Aj)

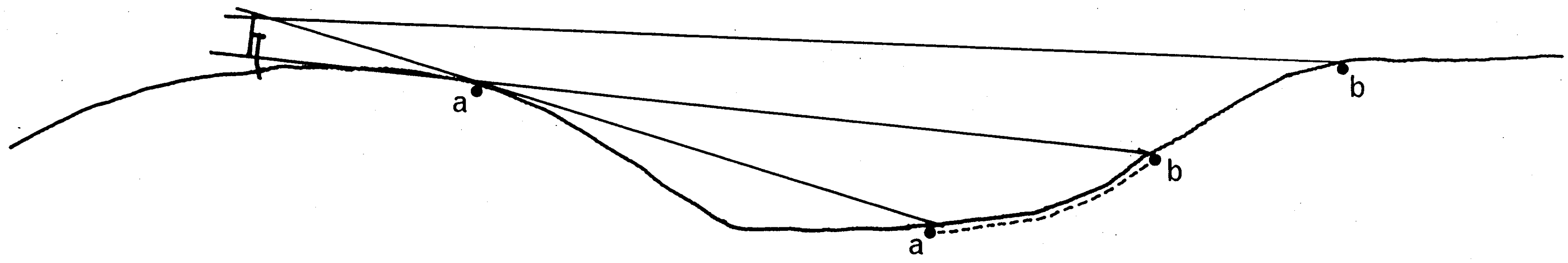
Fog and light rain have frequently been reported to reduce rates of sound attenuation, but there is no physical justification for this per se. It may arise because of reduced outdoor activity at these times resulting in lower ambient noise levels, or from changes in wind shear, or temperature changes with height.

Sound carries well when it is channelled between the ground surface and a low level, reflecting layer in the atmosphere. This happens during a temperature inversion. The statistics for the frequency of conditions likely to give rise to temperature inversions are available for Kehelland (near Camborne) during the years 1976 - 1981. These are based on upper air readings:

Season	Position Of Inversion Base	Percentage of Time At midnight.	At midday.
March April May	Above surface and below 950mb or 500m	14%	14%
June July Aug	ditto	14%	12%
Sept Oct Nov	ditto	12%	10%
Dec Jan Feb	ditto	10%	8%

Topographical Effects (Aj)

Consider the case of typical hill and valley cross sections in figure 3i. The ground between a and a will have excess attenuation but this does not apply to the line of sight situation between b and b. Exactly this topography allows the author's turbine to be heard further away in one direction than would have been the case over level, or convex ground. A similar mechanism in a concave valley appears to be in operation with the US Windpower site near Livermore California. Hubbard and Shepherd (1982). These focussing effects cannot be applied to the general case and more work is needed on the subject to guide the siting of specific turbines.



Turbine Noise: Topographical Effects

Figure 3i

Summary Of Attenuation With Distance

Whilst hemispherical spreading and air absorption can be applied to the general case, attenuation arising from barriers and climatic conditions (other than inversions) are too site, or time, specific. Wind profile and ground absorption effects both affect wind turbines. However, the mathematical models, to quantify their value, do not treat the case of a wind turbine with sufficient accuracy.

Therefore, the field data was examined to see how it would compare with attenuation based solely on atmospheric absorption and hemispherical spreading :

Table 3.2. Measured Rates Of Noise Attenuation Downwind From Wind Turbines

Machine	Near Field Trend	Middle Field Trend <10 diameters	Far Field Trend >10 diameters
Windpower.1	At a wind speed of 10m/s at hub height there was a 3dB per doubling of distance out to about 2 diameters	6dB per doubling of distance plus 1.8dB over 140m out to about 10 diameters	20dB per doubling Convex terrain
Prediction:		41.5dB(A)	
Measurement:		39 dB(A)	
Windpower.1	At a wind speed of 6m/s - ditto	6dB/doubling plus 1 dB per 140m	9 then 12 dB/dblg. Convex, then level terrain.
Prediction:		35dB(A)	
Measurement:		34dB(A)	
MOD.1			about 3 dB/dblg

Table 3.2 (cont)

Machine	Near Field Trend	Middle Field Trend < 10 diameters	Far Field Trend >10 Diameters
MOD.2	Ditto	6dB/doubling plus 2dB over 700m.	12dB/dblg Level then convex
Prediction:		48.8dB(A)	41.2dB(A)
Measurement:		48.5dB(A)	39.2dB(A)
HMZ 22.5m	Ditto	No information	
US Windpower	No information.	Just under 6dB per doubling	3dB/dblg to 66D. Broad valley
Prediction:		39dB(A)	32.3dB(A)
Measurement:		40.5dB(A)	36.2dB(A)
Hamilton Standard WTS-4		6dB/doubling plus 1.5dB over 750m.	3db/dblg
WEG MS1			<6db(A) per dblg.
WEG MS2	No information	6dB/doubling	<6dB/dblg
Prediction:		60dB(A)	53dB(A)
Measurement:		60.2dB(A)	53dB(A)

This table suggests:

Near Field: Attenuation rate to two diameters from source: 3db per doubling of distance.

Middle Field: Attenuation rate from two diameters to about ten diameters from source: Use 6dB per doubling and the effect of atmospheric absorption at a rate of 2dB per 1000m.

Far Field: Attenuation beyond about ten diameters: In this zone the figures do not give a consistent picture and the possible reasons for this are now reviewed.

Low Frequency Wind Turbine Noise And Far Field Attenuation

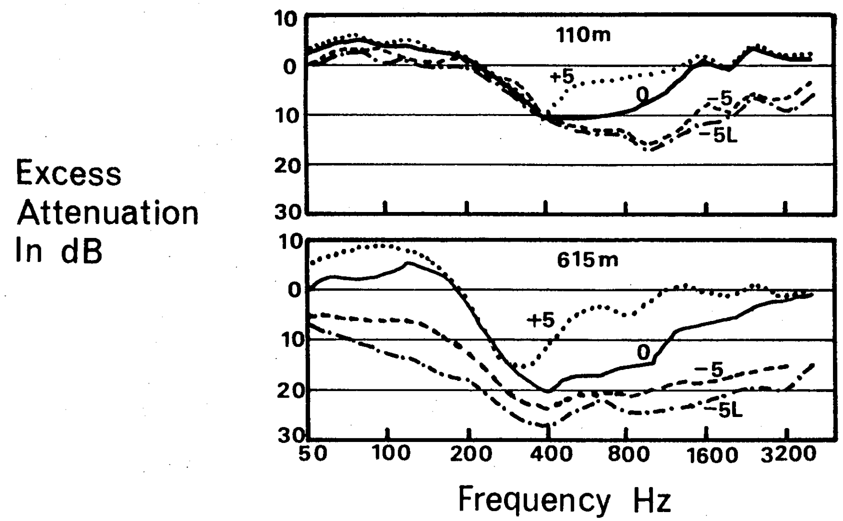
The rate of attenuation for WP1 is very rapid. It varies from 9dB(A) per doubling in distance in light winds when moderate wind shear occurs, to as much as 20db(A) per doubling of distance in winds of 10m/s at hub height during conditions of stronger wind shear.

The distance to the threshold of aural perception was checked in a number of different directions with varying terrain shapes. Although the shape of the terrain conditioned the rate of attenuation, in all cases this rate always rose to 12db(A) per doubling of distance in the far field. Some additional cause appeared to be implicated.

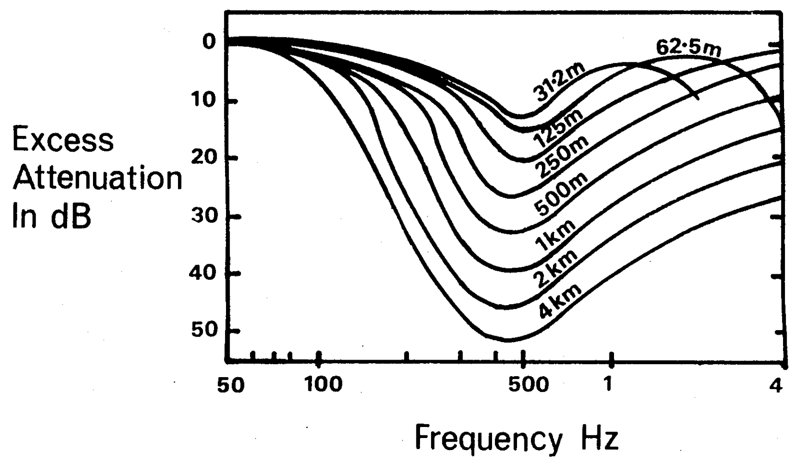
Table 3.2 shows that the MOD 2 turbine had a rate of attenuation midway between that of the WP1 and the two WEG machines. US Windpower and the Hamilton Standard wind turbines had a rate of attenuation of only 3db per doubling in distance in the far field with result that the USWP turbines could be heard at about three times the distance of WPI, even though the overall source level was similar. Shepherd (1985 and 1983) and Hubbard and Shepherd (1982) say this is a consequence of low frequency noise from the blades interacting with the wind speed deficit when rotating down wind of the tower structure. This gives a characteristic thumping sound which has been a source of annoyance and complaint. Although the frequency of blade passage is well below 20 hz, or the threshold of hearing, this downwind thumping sets up tones with multiples of the blade passage frequency at up to about 50hz. It is in this range that many of the rotating machinery frequencies are concentrated and which then coalesce with blade passage frequency.

It has been found that the low frequency part of the spectrum attenuates with distance at a lower rate than for frequencies over about 200hz as shown in figure 3j from Piercy, Embleton and Sutherland (1977). The authors say that low frequency sound waves are not refracted either by temperature or wind shear to the same extent as frequencies in the range 200hz to 2000hz. This is because the scale of the strong shear and temperature gradients near the ground become small compared with the wavelength of sound at low frequencies. Similarly, the sharp increase in attenuation with frequencies in the middle range from 200 to 2000 hz is explained as the absorption of the energy of the refracted surface wave by the viscous flow of air in the pores of the ground and in surface vegetation.

Excess Attenuation (f) Frequency



Excess Attenuation Over Grassland (f) Frequency



Source: Piercy et al 1977

Figure 3j

This is exactly the condition in the far field where the angle of elevation to the sound source has fallen to its lowest value and the impedance of the surface coupled with the effect of refraction will have its greatest effect.

Therefore, if we could design a wind turbine for which the low frequency part of the spectrum was reduced this would enhance rates of attenuation in the far field. The three main sources of low frequency noise from wind turbines are:

1 Blade thumping due to either downwind or upwind tower wind velocity deficit.
2 Rotating machinery.
3 Inflow turbulence on the blades.

The design of WP1 addressed the first cause by placing the rotor x 1.3 tower diameters upwind of a slender tower. This compares with a ratio of 1.0 on MS1 and 1.15 on Danwin machines, 0.7 on Wind World turbines and 1.27 on the MOD 2. No tower thumping is audible on the author's machine and only occasionally on the MOD 2 - presumably when the teeter hub allows the blades to pass closer to the tower.

Rotating machinery noise was reduced by 25dB worth of sound attenuation measures designed to isolate and insulate the machinery elements.

The effect of inflow turbulence was partially reduced by using a relatively low tipspeed of 54m/s. Further reductions may have been achieved by using a thinner aerofoil, but this was rejected on structural grounds.

As a result of these three measures, low frequency emissions have been suppressed. This can have a double benefit because Broner (1978) has shown that there have been an increasing number of complaints about sources which are unbalanced towards low frequencies and which exhibit a spectrum which shows a general decrease of sound pressure level with an increase in frequency. This type of noise appears to have a higher annoyance value for some people than the mean dB(A) value would suggest. By reducing the low frequency content the character of the noise can be made less annoying.

The effect of suppressing low frequency noise on WPI shows itself by comparison with other turbines in two ways:

1. If the noise spectra for WP1 and the other machines in table 3.2 are all normalised to a common datum at 250 hz frequency (or even the 1000, 500, or 125 hz frequencies) it

Wind Turbine Noise Spectra Normalised To The 250 Hz Amplitude

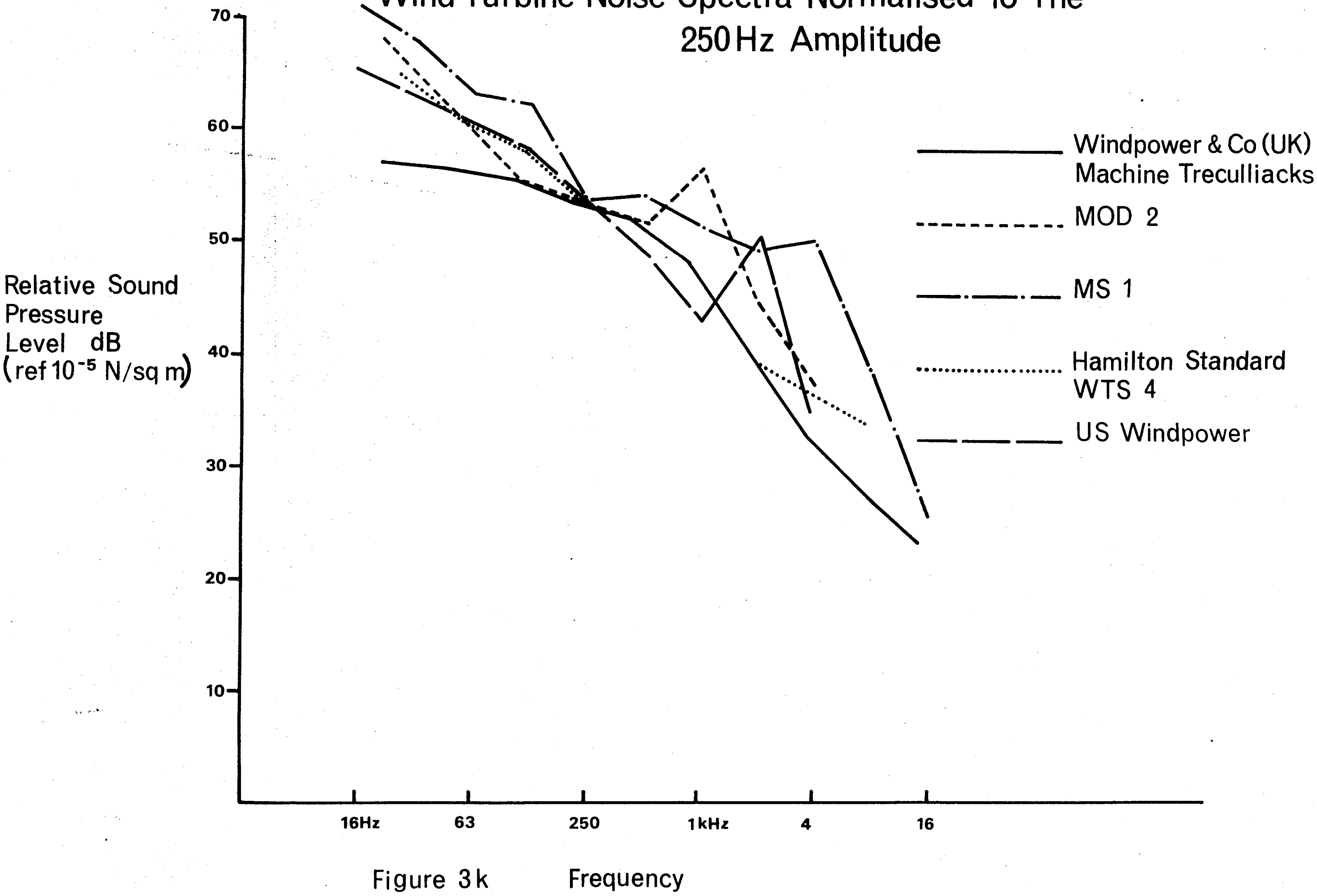


Figure 3k

shows that the contribution to the overall noise from low frequencies in the WP1 spectrum is less than for any other machine. See figure 3k.

2. A graph of the noise spectra for the machines can be drawn on clear paper and then moved up and down the Y axis to see which frequency is the last one to be heard against either the noise spectra for potential wind energy sites in Cornwall, or against the biaural minimum field. See figure 3l. WP1's last audible frequency is at about 500 hz, whereas the other machine's last audible frequency is in each case less than 200 hz. The high frequency trailing edge noise from the MOD 2 gives a 1000 hz for that machine as the last audible frequency, and low frequencies are not as prominent in its spectra as is the case with the other machines listed in table 3.2.

The conclusion is that since the last audible frequency for WP1 is also the frequency which attenuates best over grassland then this points to the reason why WP1 has the fastest rate of attenuation in table 3.2. Similarly, the turbines which are heavily weighted towards the low frequency end of the spectrum such as the USWP and Hamilton Standard machines are those with the least favourable far field attenuation characteristics.

More work is needed to better define the mechanisms of noise attenuation in the far field, but based on the limited information already available and solely for the purposes of this study the following rates of attenuation are used in estimating the gross achievable resource in Cornwall:

Table 3.3. Far Field Attenuation For Wind Turbines (>10 Diameters From The Machine)

State-of-the-art machine: 6dB per doubling in distance plus atmospheric absorption at rate of:

1000m	2dB
2000m	5dB
5000m	15dB

Quiet Machines: 12dB per doubling in distance, plus atmospheric absorption at the above rates. These figures are used in this report.

Figure 3m was compiled from these figures to determine the predicted size of the noise footprint for new, quiet machines. The literature sources from which table 3.1 was compiled were used for predicting the size of the noise footprint for existing turbines. This figure shows that noise from large machines affects more square metres of

Background Noise Level Compared With WP1 Frequency Spectrum

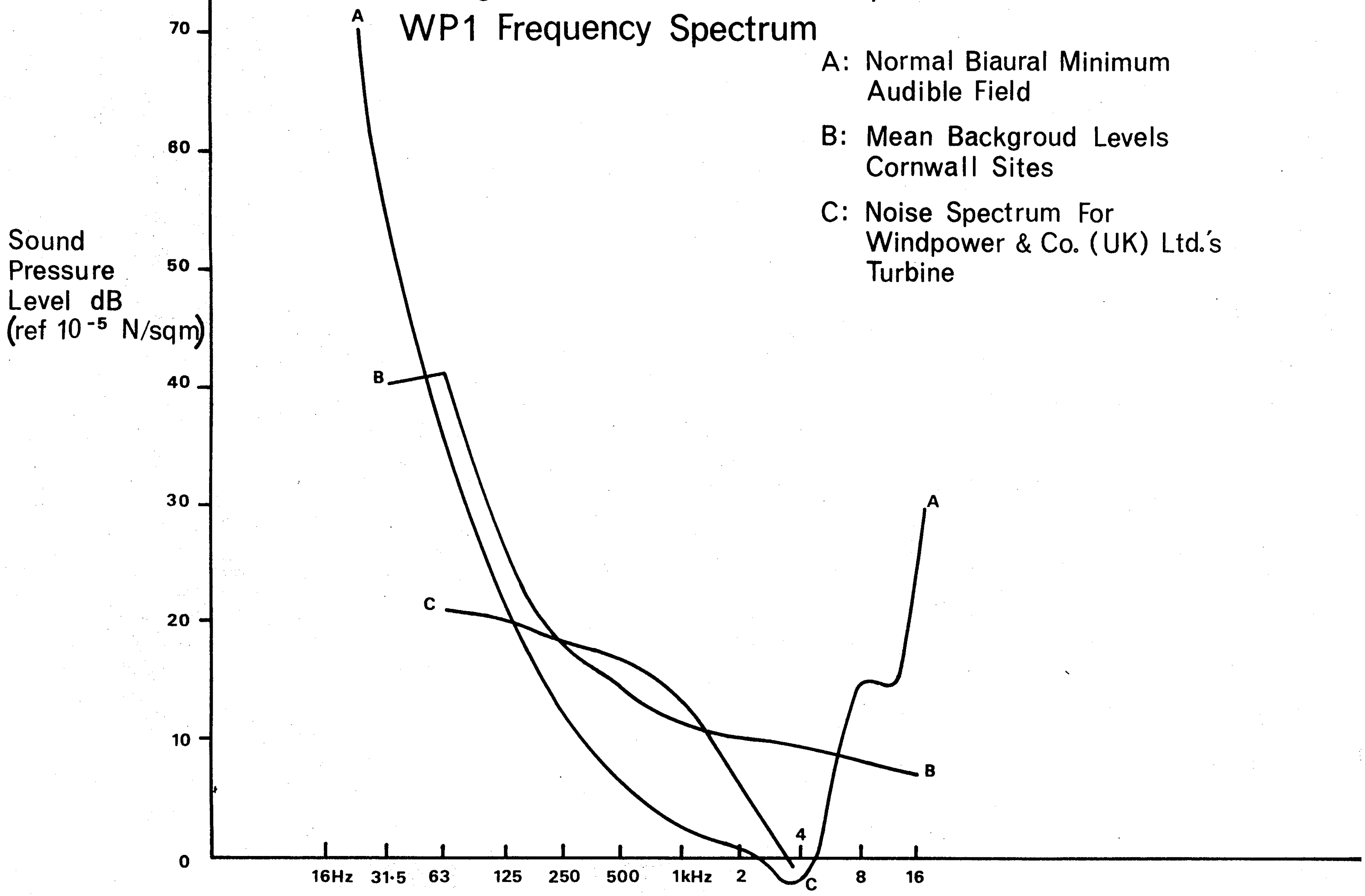
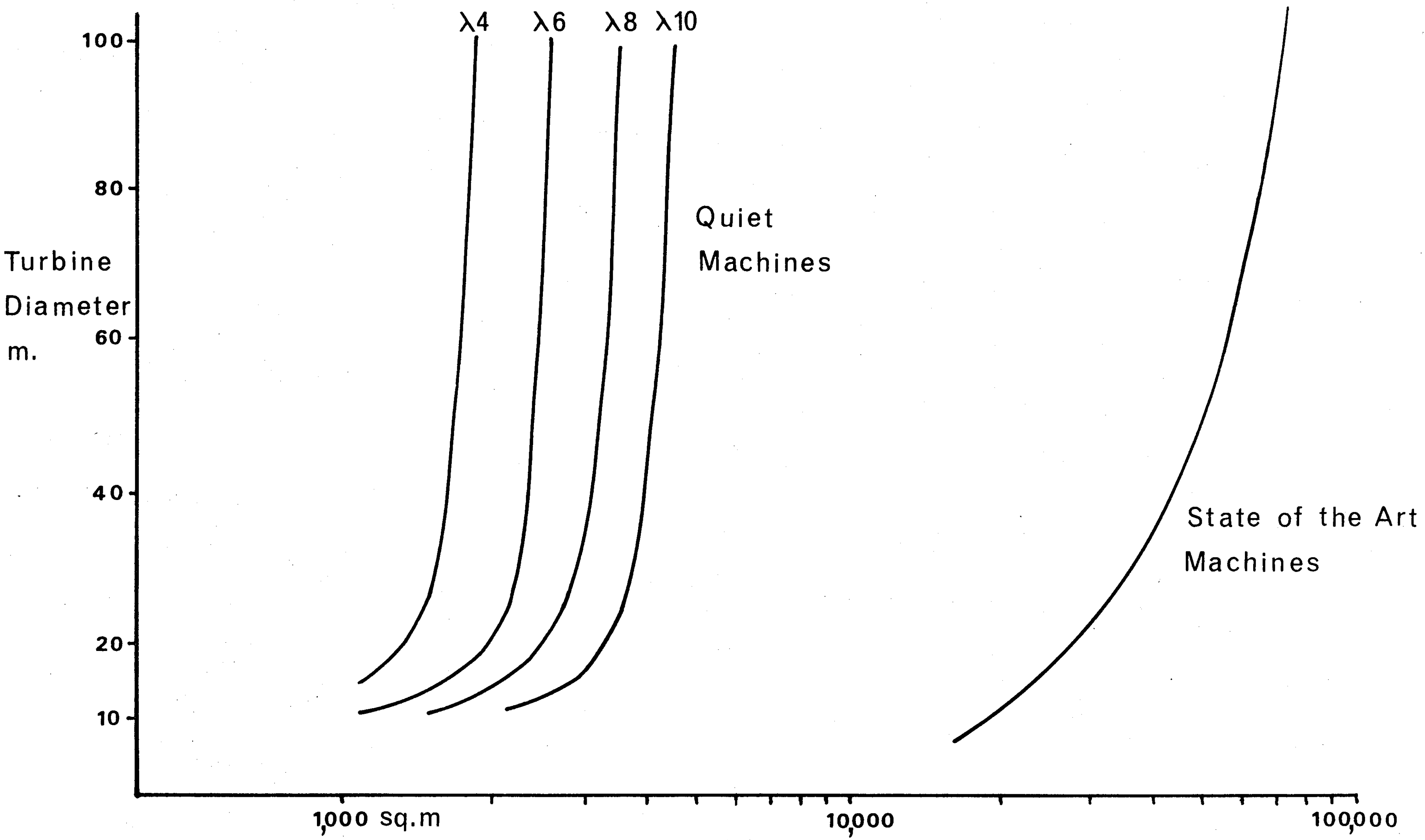


Figure 31 Frequency



Area Of Land Affected By Noise Per KW Installed (f) Diameter

Figure 3 m

land per installed kW than noise from small machines. This is partly because larger machines raise the noise source to a higher level above the ground and so reduce the effect of ground absorption.

The Threshold Of Aural Perception

If one walks downwind from a turbine taking noise readings at regular intervals, one comes to a position (190m to 220m on level ground for WP1 in up to 10m/s wind speed) when the noise levels as recorded on the meter no longer fall with increasing distance from the machine. The position at which this happens is where the ambient noise level is approximately equal to that of the turbine. Figure 3n.

However, beyond this position, the turbine can still be heard. In normal atmospheric conditions and without terrain focusing effects, one can hear WP1 for a further 140m before it becomes inaudible. The position at which this happens is the mean of a number of points since turbulence and other atmospheric inhomogeneities cause the position of the threshold of aural perception to fluctuate by plus or minus about 25 metres. The distance at which a turbine cannot be heard is an important value. Beyond this distance one would not expect valid complaints about noise. If it was possible to site turbines such that habitations and any other heavily frequented areas were normally beyond this threshold, then no wind turbine noise problem would be deemed to exist. Stephens et al, (1982) recommend that wind turbines should be inaudible at any habitation.

This threshold was recorded for WP1 from the average of two observers' results for a variety of conditions as shown in figure 3o. Note how figure 3o shows that only conditions at wind speeds below 10m/s are relevant. Above 10m/s, the ambient noise levels start to rise at a rate which reduces the size of the noise polars. (During these observations all three direct ventilation hatches were open and the machine was emitting a pure tone due to the excitation of the disc of the disc brake at its natural frequency. This was caused by the axial natural frequency of the disc having the same value as the number of slots divided by poles multiplied by rotational speed. With this condition cured and all direct ventilation hatches shut the threshold distances should be shorter at approximately 270m.)

Two questions arise: How do spot measurements taken on a few occasions represent the situation over a period of a

Quiet Machines. Distance to Detection Threshold.
(f) Diameter (f) Tip Speed Ratio.

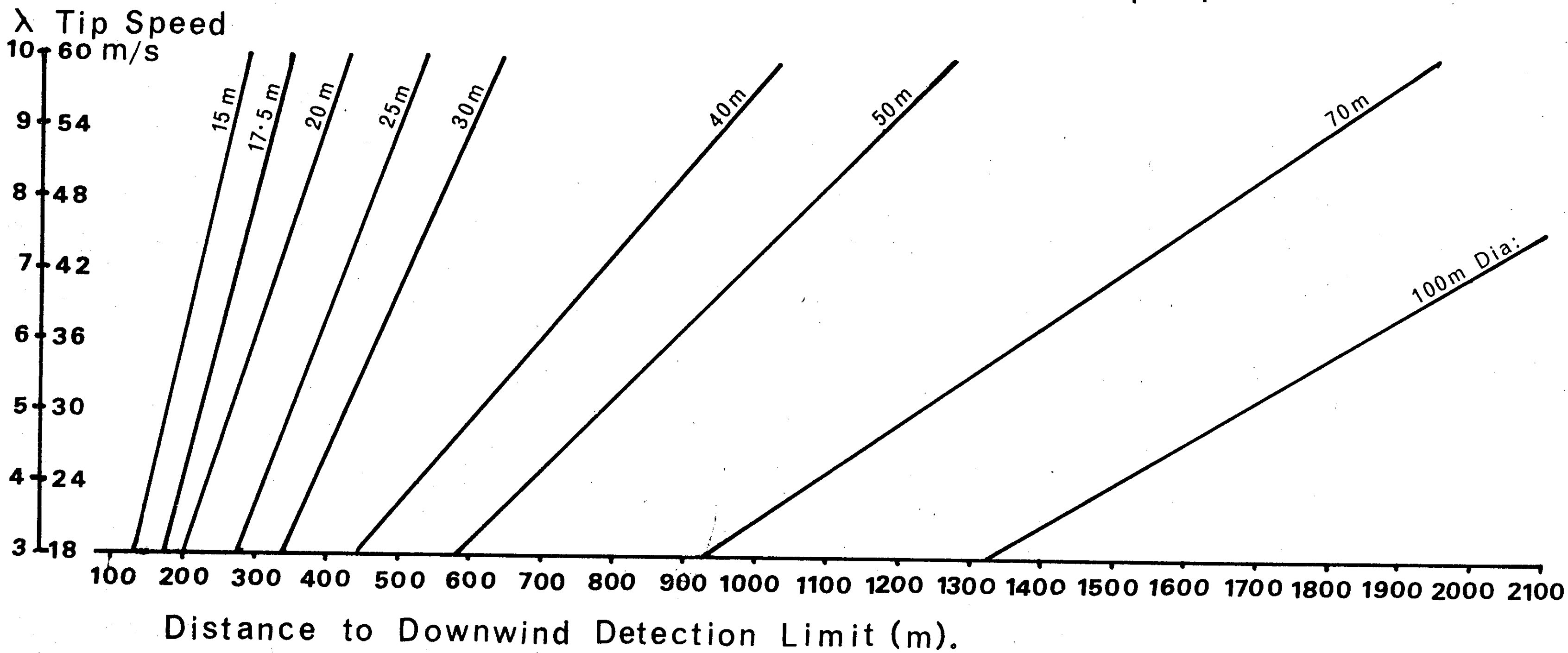


Figure 3n

Thresholds Of Aural Perception (f) Windspeed.

Windpower & Co.(UK) Ltd's. 17·5m. 145kW. Turbine at Treculliacks, Cornwall. (54m/sec. Tipspeed). Daytime Conditions.

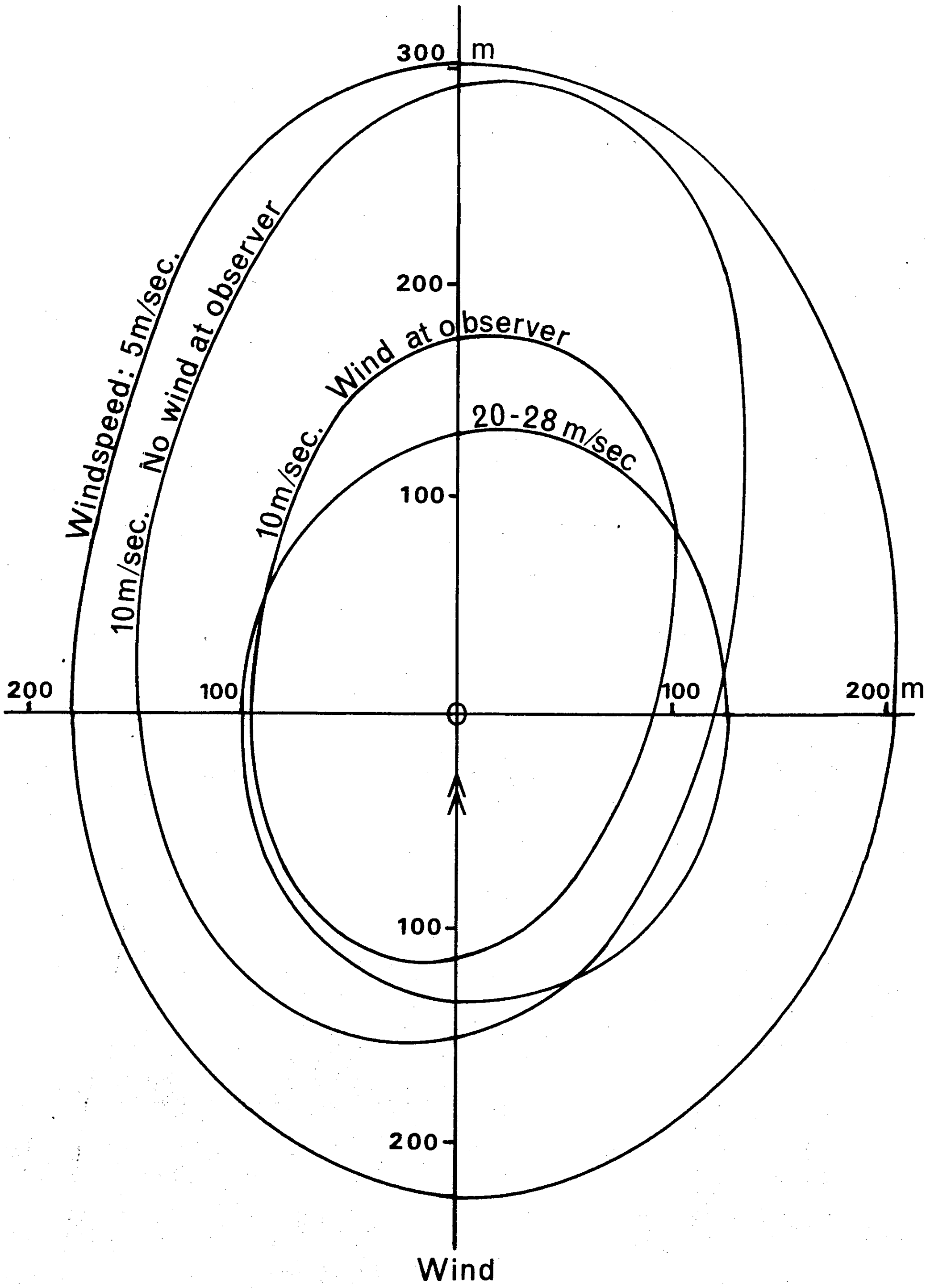


Figure 3o

year or more? For example, Windpower staff recorded a maximum detection threshold of 800m during an inversion. Were these conditions sufficiently frequent to be noticed by properties within this range?

A survey was made of 24 habitations within about 1 kilometre of the author's turbine. Apart from the terrain reduced attenuation mentioned on page 3.24, two men reported hearing the machine beyond the distances recorded by Windpower. In neither case could their wives hear the sound. It was concluded that the transient effect of inversions was not a very important issue and is ignored for the purpose of this study.

By extrapolation, on the graph of sound pressure level (f) distance from the turbine it appeared that the detection threshold was up to about 6db(A) below ambient.

The public perception survey showed that MS1 on Orkney, a 20m diameter, 250kW machine with a tipspeed of 88m/s, can be heard at distances of over 2.4km and WEG's MS2 at Ilfracombe can be heard at over 1.9km. The MOD 2 in Washington, USA has a detection threshold of 3.3km downwind and 1.3km in the crosswind direction in ambients of about 30dB(A). LS1 on Orkney (60m dia, 3MW) is audible both indoors and out of doors at a distance of 2km in the crosswind direction, but no downwind figures are yet available.

3.4.3 Ambient Noise Levels

Over forty readings were taken in association with Tala kite ascents so that the ambient, or background noise level could be discerned as a function of the wind conditions which would cause generation. The observation position was the nearest sheltered spot to the hilltop anemometer. The position was chosen carefully so that wind blowing over the microphone wind shield did not affect the result, but wind induced noise in the few small trees and hedgerow vegetation was audible. This was intended to simulate conditions of a hillside property close to the turbine. It is possible that lower readings would have been obtained at the nearest valley bottom.

Measurements were taken at Treculliacks, Crowan, St Agnes Beacon, The Lizard, Carnyorth Common, Trelow, Condolden, Davidstow and Cold Northcott. This variety of sites gave congruent results. Figure 3p shows the composite curve used to represent background noise levels. These are L90 readings, or the level which is exceeded for 90% of the time. This is the reading which is recommended by the amendment to BS 4142, 1975.

The work by Attenborough et al (1976) on ambient levels throughout the UK did not disaggregate readings below 36dB(A) so their results cannot be used to verify our findings. However, the graphs presented here are consistent with the readings taken by the County Noise officer at various locations throughout Cornwall. Attenborough et al noted that evening observations were 4dB lower than daytime results. This was also found to be the case in Cornwall.

It is noted that the recorded ambient levels in Cornwall are over 10dB(A) less than those shown on wind turbine test reports in Holland, Denmark and the USA. This may arise because the overseas tests were conducted in level, or large scale, landscapes where any wind induced noise tends to affect the whole land surface.

This is the opposite of the position in Cornwall which has a small scale, quickly modulating relief. A state-of-the-art wind turbine would operate at its maximum acoustical output for over 2000 hours per annum when the surrounding valley properties would be quite unaffected by wind induced noise. At the Windpower site, wind speeds at hub height have to rise above 10 m/s before any wind induced masking noise occurs at nearby habitations.

Ambient (L_{90}) Sound Pressure Levels (f) Windspeed.

Composite Curve: All Cornish Sites.

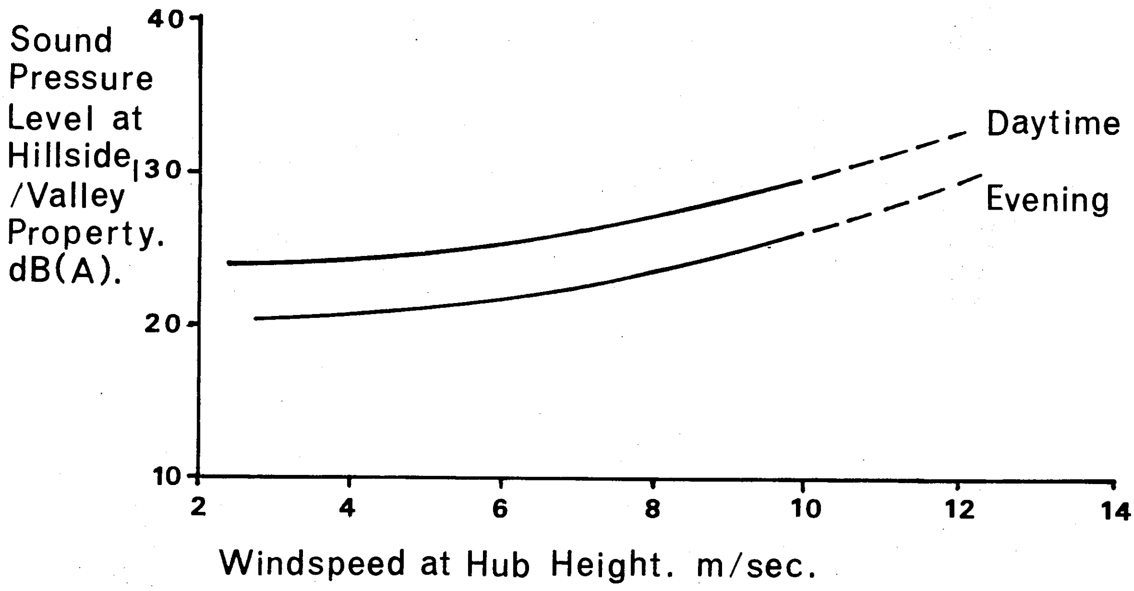


Figure 3p

Care is needed in transferring the Danish wind energy experience to UK conditions as most Danish machines have been smaller than those in this country. They have also had lower tipspeeds.

3.4.4. Contribution Of More Than One Machine

Consider that we have a single wind turbine and then, for the sake of the argument, we add another turbine in the same location. If both sources have the same sound power level then the sound pressure level at positions around the source(s) will rise by 3 db(A) for the addition of the second machine. If we have ten machines at the same location, we add 10 dB(A) to the sound pressure level for the single source thus:

Table 3.4 Noise Contribution Of More Than One Machine

1 machine:	reference	level.				
2 machines:	"	"	plus	3	dB(A)
3 "	"	"	"	4.8	"
4 "	"	"	"	6.0	"
10 "	"	"	"	10	"
n "	"	"	"	10 log n	"

We know that it is not possible to locate the additional machines in the same place as the original. If we assume that the reference machine is the turbine which is closest to the observer, then the new sum of noise will be reduced by the extra attenuation which arises on account of the increased distance between the observer and the additional machines which are situated further away.

The obvious rejoinder is: will not an observer on the other side of the array suffer from increased noise levels on account of all the machines, save the reference machine, now being closer to him? No, this does not happen because upwind propagation of turbine noise is typically less than half the distance achieved by downwind propagation. The downwind case dominates and that is the one which will determine satisfactory separation distances.

If the sound pressure level (SPL) of a single machine of the type to be installed in a windfarm is known, then Hubbard (1980) proposes the following expression based on the standard method of adding two noise sources.

From each noise source, the sound pressure level at the observer should be calculated. Then,

Total sound pressure level= $SPL = 10 \log_{10} \sum_{i=1}^{n} 10^{SPL/10}$

Where n = Number of Sources

This procedure should be repeated for all frequency bands thus yielding a sound pressure level spectrum at the receiver location. These can then be A weighted and compared with the ambient frequency spectrum to check for exceedance frequencies. If exceedance occurs, an iterative procedure is necessary which will then relocate some or all of the turbines in a different geometric pattern relative to the distribution of habitations. This is repeated until inaudibility is achieved.

By way of example, two idealised clusters of turbines of similar total site installed capacity were assessed to give downwind sound pressure levels:

Table 3.5 Comparison Of Noise From Two Different Windfarms

	Option A State-of-the-Art-Machines	Option B Quiet Machines
Radius of site:	636m	636m
Machine size:	33m diameter	17.5m
Capacity per machine:	444kW	140kW
Capacity of site:	3996kW	4205kW
Mean separation distance between machines:	7.5 diameters	6.5
Distance from observer to nearest machine:	336m	336m
Wind speed at hub height:	7m/s	7m/s
Sound Pressure Level at observer	49.5dB(A)	20.5dB(A)
Daytime exceedance over ambient:	+ 23.5dB(A)	- 5.5dB(A) (inaudible)
Evening exceedance over ambient	+ 27.2dB(A)	- 1.5dB(A)

These results show how the windfarm operator's choice of machine size and type will dramatically affect the noise levels at neighbouring properties.

3.4.5. District Council Noise Standards In Cornwall

Table 3.6 shows that the common requirement for new installations in the countryside is to have no noise above ambient at the legally owned boundary of the site.

In the great majority of cases these standards will be impossible to achieve as the turbine will often be situated on its territorial "island" only a few metres from the host leasor's land. We need an alternative standard which is still acceptable to the public. To find out what noise level would be acceptable, a public perception survey was carried out around six turbines in the UK. (See chapter 10). From this survey the following table was constructed:

3.4.6 Public Reaction and District Council Action Levels

Table 3.6

(Turbine)Noise Level	Public Reaction	Council Action
Estimated at over 10 dB(A) above ambient Noise due to traffic on newly built M40 730m from property. Report does not state exact background level.	Statutory Undertaking so claims for compensation under Part 1 of Land Compensation Act.	Tribunal awards 7.5% of house value.
10dB(A) above ambient (See Figure m)	Vociferous complainant, TV and press coverage.	Turbine restricted to daytime operation. Split vote on extension of temporary planning consent. 10dB(A) is action level for Cornwall DCs and has resulted in successful prosecutions in Magistrates court
5dB(A) above ambient	No information	Action level for one Cornwall DC
0dB(A) above ambient	No information	Typical planning requirement for legal boundary of turbine site.
0 to minus >6dB(A)	Universal and vigorous opposition to other, or further, turbines from people who have already experienced wind turbine noise of this level, some of whom are enthusistic for wind energy in principle.	Temporary planning consent only. (4 cases)

The public perception survey revealed that respondents who could hear turbine noise indoors thought this to be unacceptable. The noise level which people considered to be acceptable was one which, by interpolation, was 2 - 3dB(A) above the detection limit in the downwind sector.

3.5 Wind Turbine Noise: Conclusion

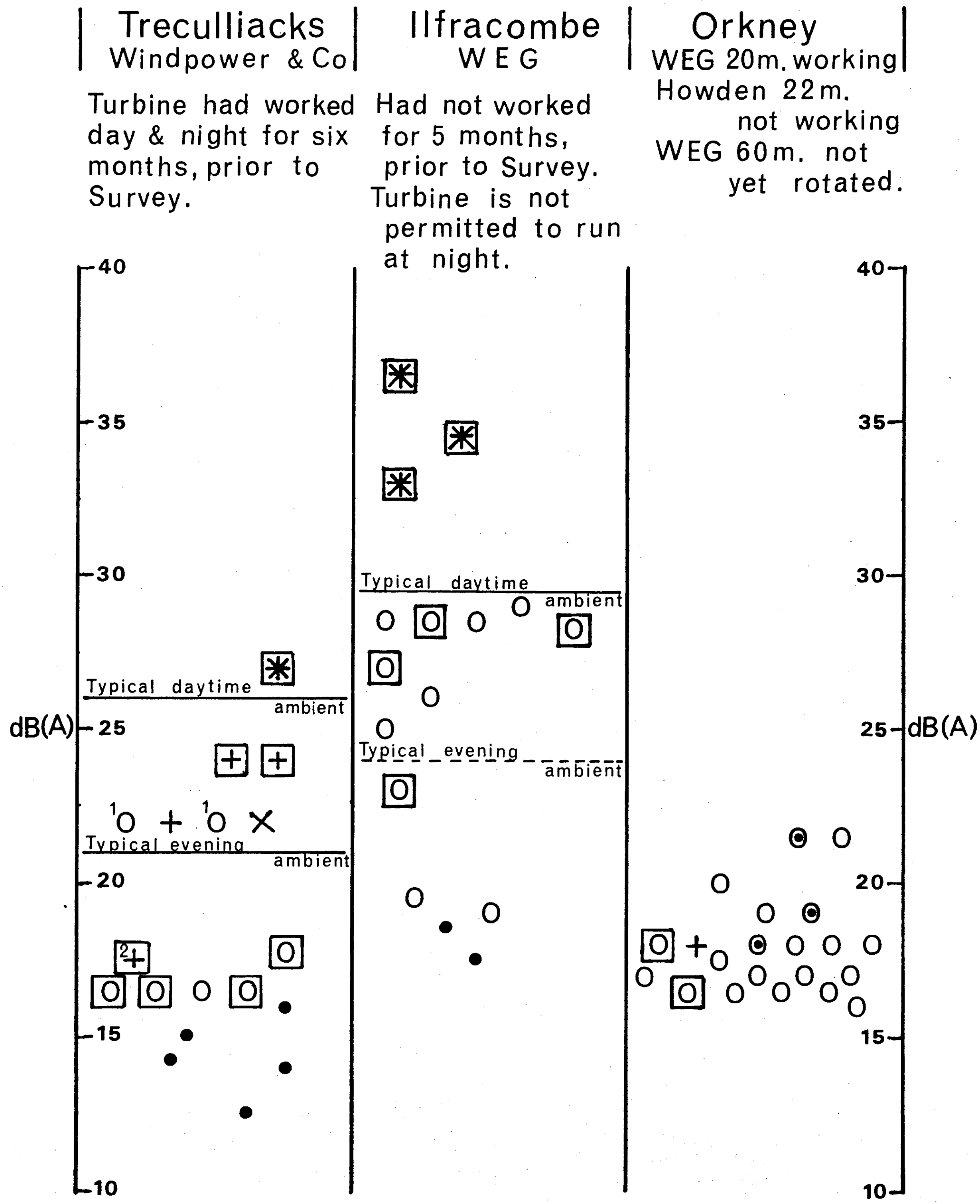
Figure 3q shows that if machines can be heard for a significant proportion of the year, even though the noise level is below ambient, then this leads to opposition to any further machines. All respondents said that noise was their main environmental complaint. If the machines could not be heard they claimed they would not object to their construction.

Although some extra effort is required in terms of design, construction cost, and siting in order to make the machines inaudible, this seems to be a very worthwhile goal if the noise problem can thereby be overcome. The resource may appear to be larger if higher noise levels are planned, but this does not warrant the adverse public reaction that it engenders.

It should be emphasised that in the case of planning for wind energy installations, this study adopts a different interpretation to that used in surveys of the public's attitude to other noise sources such as traffic and aircraft. In those cases, there is only a limited amount that public opposition can achieve. In the case of wind turbines installed and built by private companies, the decision to proceed will be largely in the hands of the District Council planning committees. To a degree they will be accountable to the residents who are complaining about potential noise nuisance. Already, District Councils in Cornwall and Devon have elected to offer temporary permissions for wind turbines in order to retain control over their impact on the locality. Consent will be easier to achieve if any reasonable grounds for complaint about the proposed installations have first been eliminated.

For turbines installed by a major utility it may be argued that the standards applicable to their other generating plant should also apply to wind turbines. Further, the asking power of a large and respected organisation, with its own special procedures for having planning applications determined, is much more likely to succeed than any private operator. Should such an installation cause noise and dominance problems and elicit an antagonistic response of the type forecast from our public perception survey, then it is less likely that the utility would either want to proceed further with wind energy, or indeed, be allowed to. More importantly, such an experience would greatly increase the difficulties of non-statutory operators then wishing to install their own machines, irrespective of their quietness or technical merit.

Public Perception Survey: Response to Noise.



Noise level in curtilage of property – downwind of turbine. Data derived from Measurements with extrapolation below ambient estimated from: 6 dB per doubling in distance, 2 dB per 1000m for atmospheric absorbtion, & 2dB for ground absorbtion, plus an allowance for barriers.

KEY: ✱ very annoyed. + unacceptable. X acceptable, but would like noise eliminated. O acceptable. ⊙ acceptable but worried about louder noise from LS.1. ● inaudible. ☐ Noise considered main disadvantage.

NOTES: 1. financial gain from wind turbine.
2. feels disadvantaged by Turbine.

Figure 3q

The maximum resource will be achieved by proceeding with the consent of the people who live around the installations and the following standard is developed with this objective. It is shown in chapter 11 that this is technically achievable within the target costs for energy supply.

3.6 Wind Turbine Noise Recommendation: The Proposed Standard For Cornwall

Wind Turbine turbine installations should be planned on the basis of being inaudible within the curtilage of any habitation or any heavily frequented area during normal operating and atmospheric conditions.

Reasons

Much of the public support for the renewables arises from their clean, non-polluting nature. To unnecessarily create noise pollution is to defeat the object of the exercise. The wind energy community has a responsibility not to annoy or antagonise its neighbours.

The amount of noise created by a machine is largely a question of choosing the correct size of turbine, designing for a quiet machine and applying sensitive siting criteria. There are no insuperable technical or economic hurdles to overcome, but as yet, the wind engineering community has not perceived noise reduction as a priority, and to date the effect of settlement patterns and topography on wind turbine design has been totally ignored.

As shown in the last section it will not normally be possible for wind turbines to comply with the usual planning requirement that there should be no noise above ambient at the legally defined boundary of the wind turbine owner's site. This rule has its origins in Common Law wherein it has been established that the occupier must keep any noxiousness within his own boundaries. Now in most instances, rural land in Cornwall not within the curtilage of any habitation has a very low occupancy level and it is a reasonable trade-off to suppress the normal dictum in favour of one which in most cases will meet the needs of the situation.

The caveat about "normal conditions" will allow occasional discrete events like shutdowns which cause a 10dB(A) increase in noise level, temporary faults, as well atmospheric conditions of limited duration like inversions, snow, fog and light rain.

The caveat about being "planned to be inaudible" recognises that noise issues in general are subject to a number of factors which cannot yet be quantified with complete accuracy. It is likely that some machines will be heard. By planning for inaudibility it is intended to minimise both the duration and degree of exceedance above the detection threshold.

In the early years, when all the potential sites are empty, it is entirely practical to follow the above standard. Only in the light of that experience should consideration be given to any relaxation in order to maximise the resource.

Some small reduction of separation distance is achieved by exposing properties to downwind noise only. This resulted in about 1300 hours of noise at affected properties. However, none of the noise codes gives any allowance for this duration of nuisance. In Common Law, three weeks has been established as the dividing line between temporary and permanent noise nuisance.

The noise output from state-of-the-art machines is shown in figure 3a and in order to determine what degree of reduction of sound power levels could be achieved a programme of noise research was carried out. Williams (1988). This showed that a 13dB(A) reduction in levels at affected properties was possible.

20dB(A) has been used as the detection threshold and 13dB(A) potential attenuation has been used for determining separation distances in this report. Figure 3m is based on these values and shows predicted detection distances for single, quiet machines.

3.7 Wind Turbine Noise: Infrasound

Below about 20 hz sound pressure waves cannot be heard by humans, but if these are of great intensity it is believed that they can have adverse affects. There was a press report by Tucker (1978) claiming that infrasound caused momentary giddiness at a distance of 40 metres from Sir Henry Lawson-Tancred's machine at Boroughbridge, and certainly the people working very close to Shapiro's machine at Elford complained about its operation. (Personal communication from Dr J Armstrong) The symptoms of infrasound are said to be a malfunction of the balance mechanism of the inner ear, fatigue or nausea, and a condition similar to drunkenness. The site hut at the Windpower's turbine is 23 metres from the tower. The only symptom noted by people spending up to eight hours there is one of fatigue. There is no way of knowing if this was caused by the turbine.

Johnson, (1976) in his survey of infrasound, claims that levels below 130dB are quite innocuous and infrasonic levels of 140dB were considered safe for the crew of the Apollo rocket. In the infrasonic range of 150dB to 153dB humans can feel their abdominal walls moving, but large animals have been exposed to 172dB without discernible effect. NASA reports infrasonic levels of 75dB to 78dB at 30m from the MOD 0 turbine and the levels around turbines of medium size should be compared with the fluctuations in pressure of about 125dB that occur naturally on a windy day. A man jogging encounters a 90dB infrasonic exposure simply because of barometric pressure variations as his head changes altitude. The implication is that the level of exposure to humans more than 1 to 2 diameters away from the size of machines likely to be used in Cornwall are harmless; but there is a paucity of data on the subject.

3.8 Wind Turbine Noise: Conclusion

Wind turbine noise is a serious impediment to wind energy development. To overcome the problem, new machines need to be developed whose primary design goal is to reduce noise levels at nearby habitations.

Operators will have to use quiet machines in the 15m to 22m diameter range in order to achieve the noise standards desired by the public. State-of-the-art machines do not meet the noise standards already established by District Councils in Cornwall. This is graphically illustrated in figure 3r.

Wind Turbine Noise Attenuation (f) Distance

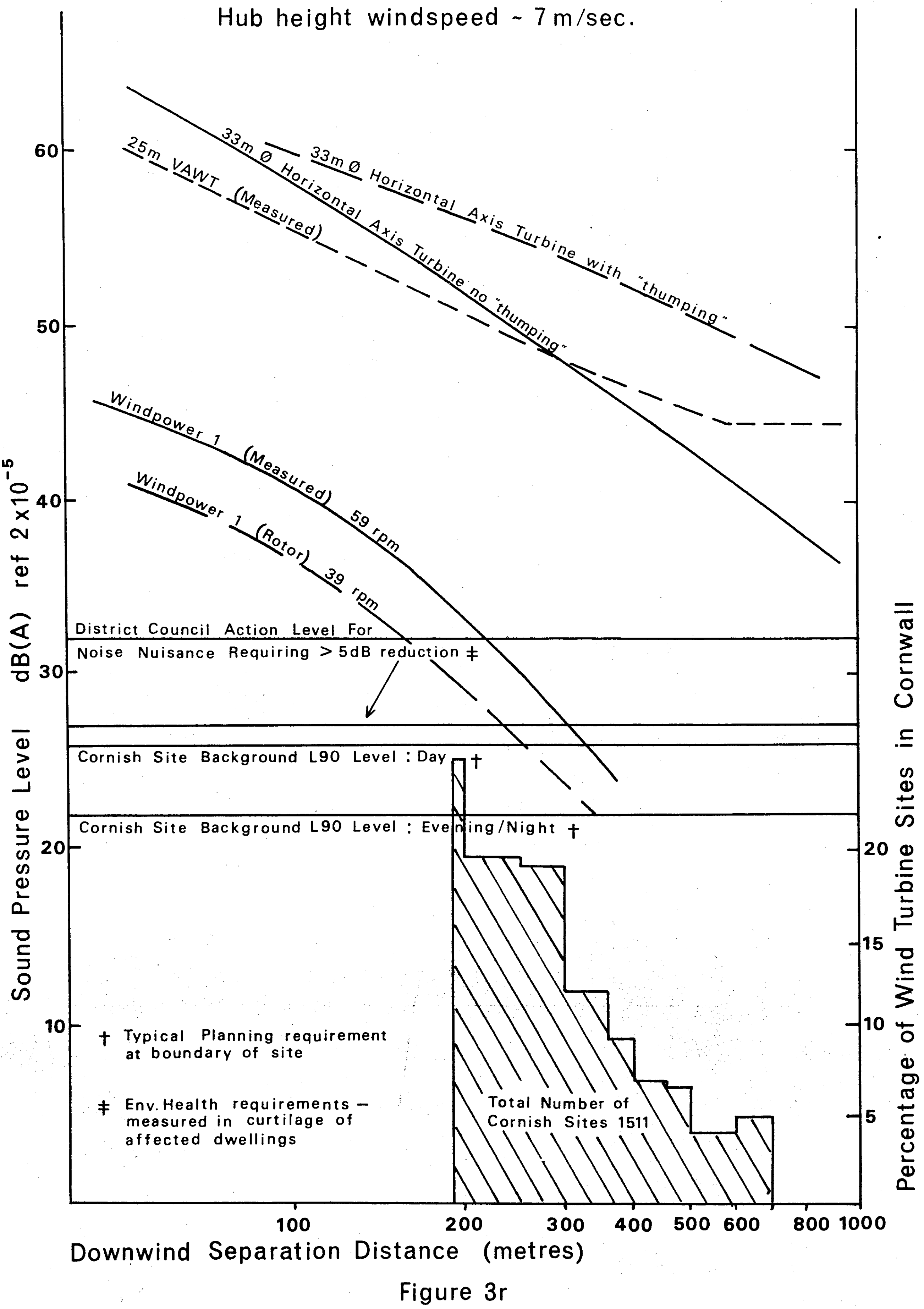


Figure 3r

Wind Turbine Noise References

ANDERSEN, B., JAKOBSEN, J. (1983)
"Noise emission from wind turbine generators." A measurement method. Danish Acoustical Institute Report No.109

ARAVAMUDAN, K.S. et al (1978)
"Wind tunnel investigations of model rotor noise at low tip speeds." NASA CP 2052.

ATTENBOROUGH, K., et al (1976)
"Background levels in the UK". Journal of Sound and Vibration. Vol.48(3), pp 359-375.

BALOMBIN, J.R.
"An exploratory survey of noise affecting mixed residential and industrial areas."

BRITISH STANDARD 4142 : (1967 (plus amendments 1975))
"Method of rating industrial noise affecting mixed residential and industrial areas."

BRONER, N. (1981)
"A criterion for low frequency noise annoyance." Bulletin of the Australian Acoustical Society. Vol.9 No.2, pp 20-27.

BROOKS, T.F., HODGSON, T.H. (1981)
"Trailing edge noise prediction from measured surface pressures." Journal of Sound & Vibration, Vol.78(1), pp 69-117.

DE BRUIJN, A., STAM, W.J., De WOLF, W.B. (1984)
"Determination of the acoustic source power levels of wind turbines." European Wind Energy Conference, Hamburg, pp 889-894.

DEPT. OF NAVY REPORT
"Acquisition, reduction and analysis of acoustical data." NADC-AWG-50.

FASOLD,W., og KRAAK W., and SCHIRMER W. (1984)
Taschenbuch Akustik. VEB Verlag Technik, Berlin.

ELLISON, A.J. (1968)
"Acoustic noise and vibration of rotating electric machines." Proc. IEE, Vol.115 No.11, 1968, pp 1633-1640.

ESTATES GAZETTE. (1978)
"Compensation claims: lands tribunal decisions." Barb v. Secretary of State for Transport. Rigby v same. August.

GLEGG, S.A.L., et al (1984)
"Noise prediction programme for wind turbines." Department of Energy Report No. TWC P 8218.

GREENE, G.C., HUBBARD, H.H. (1980)
"Some calculated effects of nonuniform inflow on the radiated noise of a large wind turbine." NASA TM 81813.

GUSTAVSSON, B., TORNKVIST, G. (1978)
"Test results from the Swedish 60kW experimental wind power unit." D1-1. International Symposium on Wind Energy Systems, Amsterdam.

HAYDEN, R.E. ARAVAMUDAN, K.S. (1978)
"Prediction and reduction of rotor broadband noise." NASA CP 2052 Part 1, 1978.

HOUSE, M.E.
"Rotor noise." Wolfson Unit, Southampton University Institute of Sound & Vibration Research.

HUBBARD, H.H. (1953)
"Propeller noise charts for transport airplanes." NACA TM 2966, June.

HUBBARD, H.H. et al (1983)
"Noise characteristics of large wind turbines generators." Noise Control Engineering Journal Vol.21(1), pp 21-29.

HUBBARD, H.H. et al (1981)
"Sound measurements of the MOD-2 wind turbine generator." NASA CP 165752.

HUBBARD H.H. and SHEPHERD K.P. (1982)
"Noise measurements for single and multiple operation of 50kW wind turbine generators." NASA-CR-166052. December.

HUBBARD H.H. and SHEPHERD K.P. (1980)
"Prediction of the far field noise from wind energy farms." (Bionetics Corp) NASA-CR-177956. April.

JOHNSON, D.L. (1976)
"Infrasound, its sources and its effects on man." Rep. No. AMRL-TR-76-17 Aerospace Medical Research Lab., Wright Patterson Air Force Base, Ohio.

KEAST, D.N., Potter, R.C. (1980)
"A preliminary analysis of the audible noise of constant-speed, horizontal-axis wind-turbine generators." US Dept. of Energy Report No.4281.

KELBY, N.D. (1981)
"Acoustic noise generation by the DoE NASA MOD1 wind turbine." NASA CP 2185.

KELLY, N.D. (1981)
"Noise generated by large wind turbines." Wind Energy Technology Conference, Missouri Univ., Columbia (U.S.A) College of Engineering, March.

KRAGH, J. et al (1982)
"Environmental noise from industrial plants." general prediction method. Danish Academy of Technical Sciences, Report No.32.

KRAMER, J.J. et al (1986)
"Low noise propulsion systems for subsonic transports." ASME Symposium on Machinery Noise, Los Angeles.

KRAMER, M. (1953)
"The aerodynamic profile as acoustic noise generator." Journal of Aeronautic Sciences, Vol.20, pp 280-296.

KRISTIANSEN, U.R., Pettersen, O.K.O. (1978)
"Experiments on the noise heard by human beings when exposed to atmospheric winds." Journal of Sound & Vibration, Vol.58(2), pp 285-291.

KURZE, U., BERANEK, L.L.
"Sound propagation outdoors." Noise & Vibration Control, pp 164-193.

LEVERTON, J.W.
"The noise characteristics of a large "clean" rotor."

LIGHTHILL, M.J.
"On sound generated aerodynamically."

LJUNGGREN, S. (1984)
"Acoustics. measurement of noise emission from wind energy conversion systems." International Energy Agency Programme.

LOWSON, M.V.
"Fundamental considerations of noise radiation by rotary wings."

MILLER, L.N. (1978)
"Sound levels of rain and of wind in the trees." Noise Control Engineering, Vol.11(3), pp101-109.

MORFEY, C.L.
"Rotating blades and aerodynamic sound" Journal of Sound and Vibration. Vol. 28(3), p 587.

PATERSON, R.W et al (1973)
"Vortex noise of isolated airfoils." Journal of Aircraft, Vol. 10 No.5, pp 296-302.

PIERCY, J.E., et al (1977)
"Review of noise propagation in the atmosphere." Journal of the Acoustical Society of America, Vol.61.

SCHLINKER, R.H., Amiet, R.K. (1981)
"Helicopter rotor trailing edge noise." NASA CR 3470, November.

SHEPHERD, K.P. Hubbard, H.H. (1982)
"Sound measurements and observations of the MOD OA wind turbine generator." NASA CR 165856, February.

SODERQVIST, S. (1982)
"Swedish WTG: The noise problem." Proceedings of the Fourth International Symposium on Wind Energy Systems, Stockholm.

STEPHENS, D.G., et al (1982)
"Guide to the evaluation of human exposure to noise from large wind turbines." NASA Technical Memorandum 83288.

STEPHENS, D.G., et al (1983)
Wind turbine acoustic standards. NASA TM

THOMSON, D.W., et al (1981)
"Enhancement of far field sound levels by refractive focusing." Wind Energy Technology Conference, Missouri, Columbia (U.S.A) College of Engineering pp 267.

TUCKER,A. (1981)
"The art of tilting at windmills." The Guardian. p 18, 13th December.

VDI 2159 (1985)
"Emmissionskennwerte technischer schallquellen getriebegerausche." July.

VITERNA, L.A. (1985)
"The NASA LeRC wind turbine sound prediction code." NASA CP 2185.

WILLIAMS, G. J. (1987)
"Preliminary review of the effect of wind turbine noise on the achievable wind energy resource in Cornwall." Pub Windpower & Co (UK) Ltd, March.

WILLIAMS, G. J. (1988)
"Assessment of the potential noise reduction of wind turbines designed for this purpose." GJW/21. Windpower & Co (UK) Ltd. March.

4. RADIO FREQUENCY INTERFERENCE

Abstract

Wind turbines can interfere with radio signals by blocking their path to a receiver or by reflecting secondary, unwanted signals which, being out of phase with the primary signal, distort reception. The degree of interference gets greater with increasing turbine diameter and rotor solidity, increasing blade conductivity and turbine tower height, more turbines and the increasing frequency of the signal.

The method for predicting separation zones beyond which interference is avoided are inadequate, and the methods of field survey are expensive. There is no publicly available register of emission sources and those held on a confidential basis by the Department of Trade and Industry are not comprehensive. Potential conflicts with existing radio services will not come to light through the planning consent process, and the penalties for causing interference are substantial. These range from damage to the effectiveness of safety at sea communications and of air navigation aids, to interrupting telecommunications of very high value and interfering with domestic television. The Home Office has powers to shut down any equipment which causes interference and generally it will be the responsibility of the turbine operator to avoid, or rectify, any difficulties.

The survey used the recommendations of the manufacturers of microwave equipment and the requirements of the nine operators of fixed microwave links in Cornwall. This meant that a 1km band straddling major microwave routes became a forbidden zone for wind turbines. The same procedure was followed with the operators of other radio services, some of whom asked for safety zones with a 5km to 10km radius.

The BBC terrain model may need to be used if there is any possibility of interference with the signal passed from a main transmitter to a relay station, as this could affect a large number of habitations. Otherwise, the separation distance for wind turbine noise is greater than that required to avoid domestic television reception problems except where the wind turbine is directly between the transmitter and receiver, or where reception of television signals is already weak. There are relatively inexpensive options for dealing with television interference problems.

The guidance for the safe siting of wind turbines away from locations where electromagnetic waves might cause explosions is inadequate; but the most obvious locations in Cornwall and across the Tamar are protected from wind turbines for other reasons.

Potential problems from radio interference have a serious effect on the gross wind energy resource in Cornwall. It reduced the number of prospective turbine sites from over 2500 to 1511. The rapid growth in telecommunications means that further sites will be lost every year.

It is recommended that further research and field testing be directed at compiling a turbine siting manual which can be used by wind engineers to avoid radio frequency interference problems. Any specialised equipment needed for measuring frequencies and signal strengths at potential wind turbine sites could be usefully held by instrument hire companies for use by wind turbine operators and local authorities.

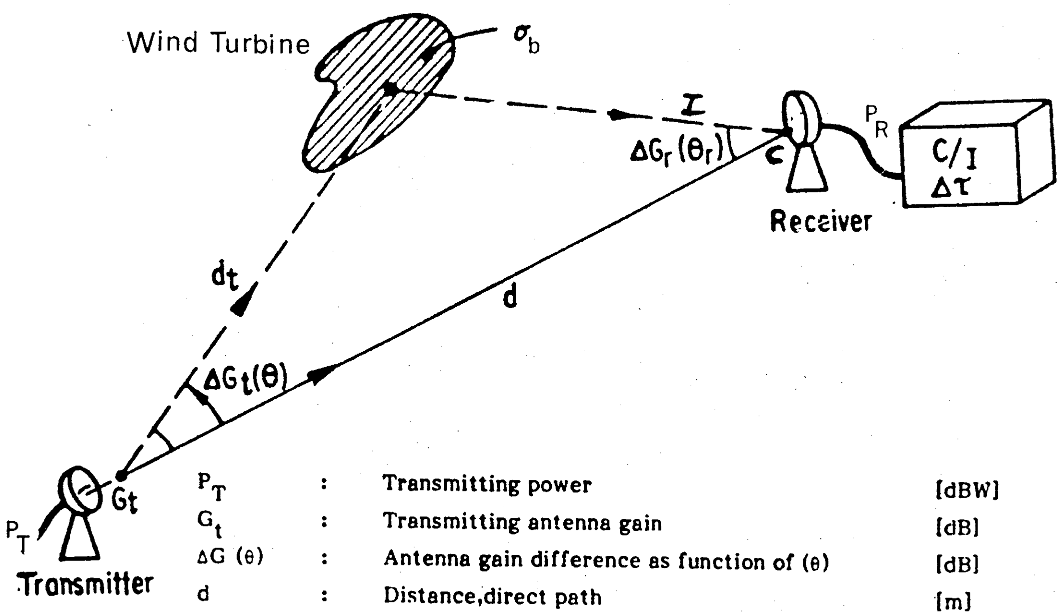
4.1 Radio Frequency Interference: The Problem

Wind turbines can interfere with the reception of radio signals. The basic mechanism is shown in figure 4a. The receiver R accepts the primary signal from the transmitter, but also receives an unwanted, reflected signal from the wind turbine. The reflection of signals from large static structures is familiar from "ghosting" on television screens. In the case of a wind turbine the rotation of the blades and causes a higher degree of signal reflection when a blade is vertical than when a blade is horizontal. Therefore, the receiver experiences an amplitude modulation of the reflected signal. Also the reflected signal arrives at the receiver slightly later than the primary signal due to its longer transmission path. This may appear as a doppler shift. The ratio between the strength of the primary signal and the strength of the unwanted reflected signal determines the degree of interference.

For amplitude modulated (AM) systems the variation in level may be the most serious effect. For frequency modulated (FM) systems, the doppler shift may be more critical. Just consider what would happen if the wind turbine is moved away from the receiver along an arc which keeps it at a constant distance from the transmitter. Then, although the strength of the incoming signal to the wind turbine remains the same, the reflected signal strength at the receiver diminishes as the wind turbine distance is increased. Finally, a point is reached when the turbine no longer interferes with reception. This distance, calculated in every direction, describes the separation zone around a receiver. Equally, this zone can be drawn around a wind turbine. In general terms the size of the interference zone increases by:

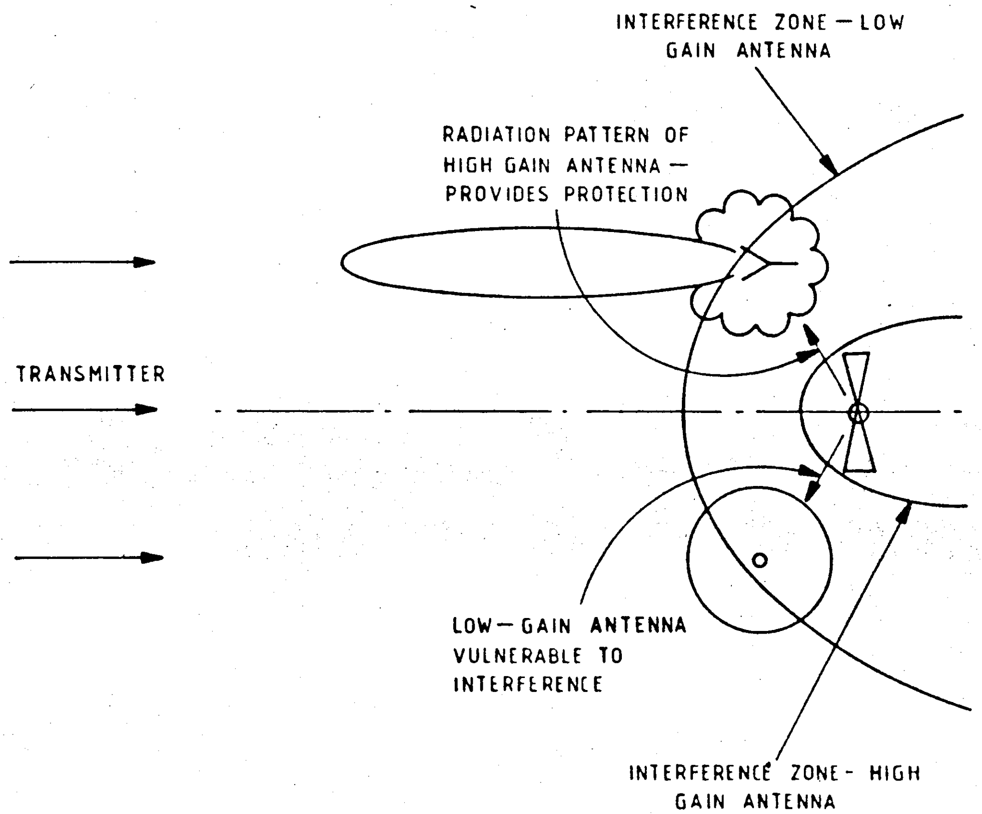
1 increasing the frequency of the radio emissions,
2. increasing the diameter of the turbine,
3. increasing the number of blades,
4. increasing the solidity of the rotor for a given number of blades at a fixed diameter,
5. increasing the height of the tower,
6 increasing the height of the turbine above surrounding receivers, particularly where the receiver is situated in a valley such that the signal was already weak before the erection of the wind turbine,
7. increasing the conductivity of the rotor blades,
8. increasing the number of wind turbines in a group, particularly if the are rotating in synchronism,
9. the inadequacy of the receiving antenna.

Chignell (1986)



P_T	:	Transmitting power	[dBW]
G_t	:	Transmitting antenna gain	[dB]
$\Delta G\ (\theta)$	:	Antenna gain difference as function of (θ)	[dB]
d	:	Distance,direct path	[m]
$d_t + d_r$	:	Distance,unwanted secondary path	[m]
$\Delta(G_r(\theta)$	:	Receiving antenna gain	[dB]
σ_b	:	Bistatic radar cross-section	[dBm²]
P_R	:	Receiving power	[dBW]
C/I	:	Carrier-to-interference ratio observed at receiver	[dB]
$\Delta\tau$	:	Time delay difference between direct and secondary paths	[sec]

4a Scattering Configuration. Source: Chignell (1986)



4b The Dependence Of The Dimensions Of The Interference Zone On Antenna Gain.

Figure 4a & b Source: Chignell (1986)

Further, the interference zone is conditioned by the radio frequency modulation scheme, the terrain pattern, the geometry of the relative positions of the transmitter, receiver and wind turbine, the rotational speed of the blades and whether these coincide with some critical frequency of the radio service, the size of the rotor relative to the wavelength, and if the wind turbine is a vertical axis or horizontal axis type.

It is important that the wind turbine operator takes full responsibility during the planning of its installation to avoid possible radio frequency interference since:

a. The services at risk could include the safety of life at sea, defence, navaids, emergency services, commercial telephone operations of very high value and television reception for a substantial number of homes.
b. Potential conflicts of interest will <u>not</u> be picked up by the existing District Council planning process.
c. If a problem arises, it will usually be settled in favour of the radio service if this was present before the erection of the wind turbine.
d. The Home Office has powers to shut down any equipment which causes interference.

The International Energy Agency has an expert group drawn together to make recommendations for the electromagnetic interference from wind turbines. The report of this group (edited by R.J. Chignell, 1986) states that the procedures for determining radio frequency interference "involve describing processes that are dependent upon a large number of variables, the relative importance of which vary widely from installation to installation in a manner that with the present state of knowledge cannot be readily assessed." As yet, there is no official guidance on the safe installation of wind turbines or wind farms with respect to radio frequency interference.

4.2 Radio Frequency Interference: The Aim

The aim was to delete any sites from the survey which may cause radio frequency interference.

4.3 Radio Frequency Interference: The Method

The following procedure was adopted to ensure that prospective wind turbine sites in Cornwall would not interfere with radio services:

1. Conduct literature search (See references at end of chapter).
2. Search for all emission sources in the county.
3. Ask these operators and the manufacturers of their equipment for full details of their services and what separation zones they would like us to observe.
4. Check these zones for reasonableness against field experience and the various theoretical treatments.
5. Plot these zones on 1:50,000 maps and delete areas forbidden to wind turbines.

This work took a long time to complete because there is no publicly available, central register of radio emission sources. The Department of Trade and Industry does maintain a catalogue of new radio antennae derived by monitoring all planning consents. However, the rapid growth of private mobile base radio stations since 1985 means that new installations since that date are not listed in the catalogue. Further, British Telecom had blanket approval to erect a particular type of microwave link and these, too, do not appear in the catalogue. During the course of our work several radio stations were discovered which were not previously known to the D.T.I.

The contents of the catalogue are confidential to the D.T.I and to the operators of the service. Therefore, we had to suggest to D.T.I the names of potential operators and if the catalogue showed that they had facilities in Cornwall the D.T.I would write to the operator describing the nature of our inquiry and ask for the operator's permission for us to write to them direct. When the search appeared to be complete the D.T.I checked our composite list, and suggested we write again to a number of operators who had seriously under-reported their network. Every operator, including the Home Office and Ministry of Defence, cooperated with our study. All operators stressed the confidentiality of the information they supplied and asked that it should not appear in any published document, therefore the map of RFI zones is not reproduced in this document. The condition of confidentiality was accepted, for otherwise very little information would have been made available to us. As this information is so quickly out-dated by new services, any operator who wishes to install a wind turbine should seek advice from the Radio Regulatory Division of the D.T.I, Waterloo Bridge House, Waterloo Road, London, SE1 8UA. The information given below is limited to that which is in the public domain.

4.4 Radio Frequency Interference: Work Done

4.4.1 Microwave Links

Microwave links are used for voice communication and data transmissions. They operate at between 1 and 30Ghz. In Cornwall there are (September 1987) at least nine operators with frequencies varying from 1.3Ghz to 19Ghz and with route distances varying from 5km to about 70km. Microwave antennae are highly directional and the line of sight beam width is generally less that +/- one degree. Interference between wind turbines and microwave communication is potentially more serious than, say, television interference as no low cost, remedial measures appear to be available. Either the turbines, or the microwave track, have to be moved. In some situations it will be impossible to move the microwave repeater because any alternative route could not avoid terrain obstacles. The value of traffic can be as high as £30,000 per hour.

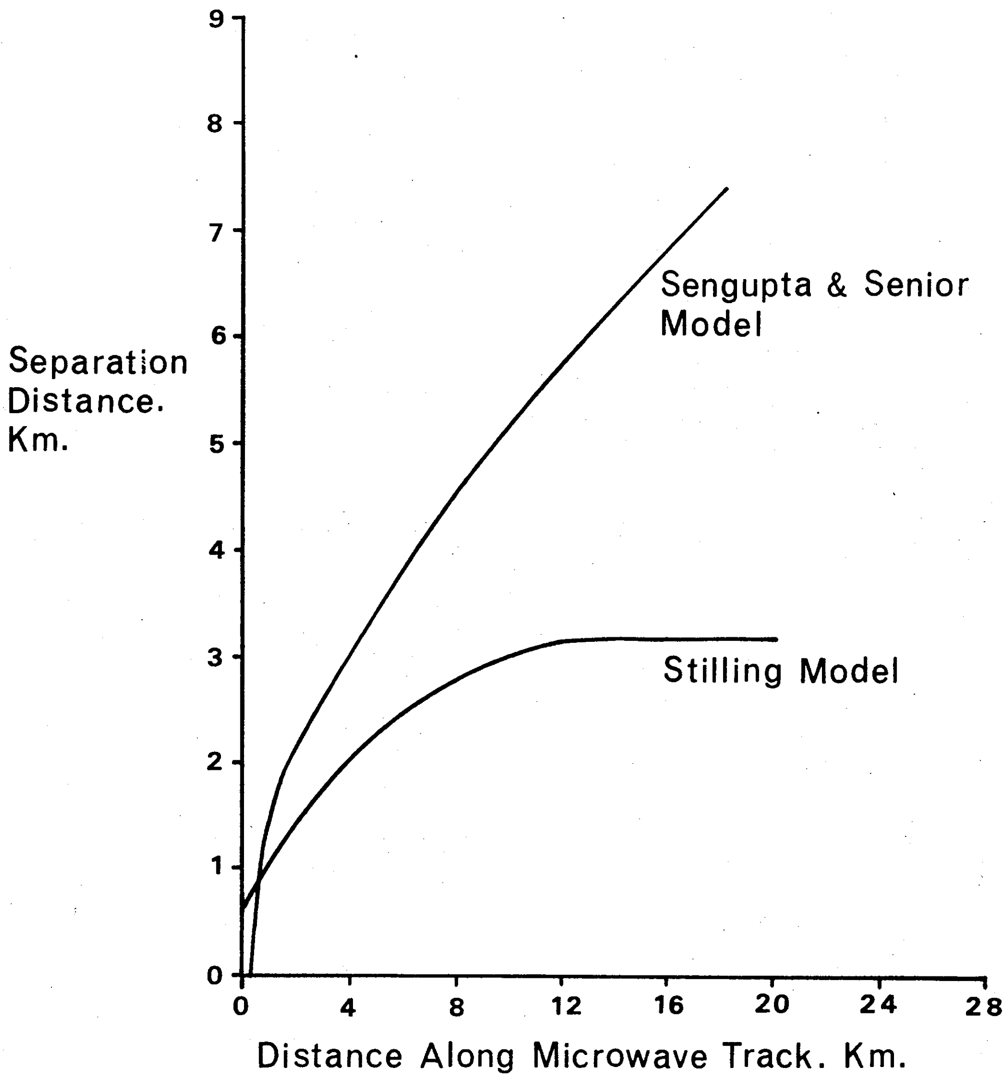
The two main models for the prediction of a safe separation zone around a microwave repeater station and the microwave route have been developed by Senior and Sengupta (1978) and by Stilling (1986). Stilling's model has been programmed and uses the results of van Katz's study and the blade reflective coefficients developed by Senior and Sengupta. Common input data was applied to both models, but they gave widely differing results - see figure 4c. The difficulty of laying down a standard separation zone for microwave routes is compounded by the fact that different equipment will be able to tolerate different interference levels and this value will also change for different operating frequencies and route lengths. The level of permissible interference below that of the carrier varied from -25 to -85dB. This has a major impact on the size of the separation zone. Voice communications are more tolerant than data transfer links which have error checking codes built into their operation, but several operators of voice links said they had plans to install data transmission.

Furthermore, the graphical representations of the safety distances should be used with care as they refer only to the so-called backscatter case where the wind turbine is situated outside the line of sight from transmitter to receiver. In the case of forward scatter when the radio signals are almost passing through the wind turbine there is at present no accurate method of calculation to decide the width of the safety zone. Instead a minimum width of 2 - 3 times the first Fresnel zone is often used for the forward scatter case. The first Fresnel zone is defined as:

$$R = \left(\frac{D_1 \times D_2}{D_1 + D_2}\right)y^{0.5}$$

where D_1 and D_2 are distance along the route to the

Comparison Of Models Predicting Exclusion Zone Around Microwave Transmitter/Receiver.



Wooden Blade with lightning protection.

Individual Blade Area : 14 sq.m

Frequency : 11·2 GHz.

Signal to Noise :−40 dB.

Figure 4c

obstruction from the transmitter and receiver respectively and y is wavelength in m. The forbidden zone is an ellipse with the ends at the transmitters and the widest point in the centre.

A precise definition of where the transition between these two scatter configurations occurs is not yet developed. (Private communication, Stilling, 1987)

Recommendations for separation distances from microwave routes made for wind surveys abroad do not give a consistent picture. Telecom Denmark recommends that no wind turbine be sited within 200m of the centreline of a microwave route. Further, a zone enclosed by a +/-3 degree vector from the microwave route should be decided on an individual basis by Stilling's method, taking into account the size and number of wind turbines as well as the shape of the topography along the route. On the other hand, Dutch PTT recommends a 600m radius around a microwave repeater/transmitter, but only 100m separation from the route's centreline.

Nor is there any field data to confirm these models or recommendations. By chance, the Windpower & Co turbine at Treculliacks is about 250m to one side of, and 15m below, the centreline of a 1.5Ghz voice link. This is beyond 60% of the first Fresnel zone required by the operator who confirms that no interference has been observed.

In the absence of a reliable model it was decided to rely solely on the requirements of the various operators of fixed links in Cornwall even though the operators admitted that these zones were based on guesswork. They gave the following distances:

Operator	Frequency	Separation From Transmitter, receiver	Distance From Route	Based On:
British Telecom	3 - 16Ghz	1km	500m	Guess
Utilities	1.5Ghz	600m	100m	60% of first Fresnel zone
Unidentified	1.7/2.3Ghz	1km	+/- 5 degrees from beam for up to 5km from transmitter	Guess

There is a need for a field tested manual which can be used by wind engineers in determining safe distances from microwave routes. At present there is no way of knowing if the requirements sought by the operators of fixed routes are accurate.

4.4.2 Other Radio Emission Sources

A similar procedure was followed for determining the separation criteria around other radio emission sources in the county:

Operator	Service	Radius	Based On
Civil Aviation Authority	VOR	1km	CAA standard criteria
ditto	ILS	500m from track to outer marker	
BT International Transmitters	Marine Radio	2km	BT requirement
VHF Radio	Broadcasting	200m	
UHF	Broadcasting	200m	
TV Relay Transmitter	Broadcasting	200m	Ilfracombe experience
TV:Redruth, Caradon	Broadcasting	1km	
Numerous unidentified operators.		Up to 10km	

4.4.3 Interference To Domestic Television

The rotating blades of a wind turbine produce a time varying amplitude modulation which can severely distort the video portion of television reception. It does not affect the audio signal. Problems arise at two levels:

1. A wind turbine, or a group of wind turbines, could interfere with the link between a main transmitter and a relay station thereby putting a large number of receivers at risk. In Cornwall, the BBC did not think that interference would occur where there was line of sight transmission between the two aerials. Interference could come about where line of sight was not achieved between the main and relay station. This occurs most frequency near the coast where reception is weakest. The BBC has a terrain model on computer and this facility is also used by the IBA. This would need to be invoked before the installation of any turbine. It is not expected that this will make very much difference to the total resource as it will often be possible to move potential wind turbine sites to other nearby positions which do not cause interference.

2. Turbines could directly affect the signal at neighbouring habitations. While the blades are stationary the scattered signal may appear as a ghost and this fluctuates as the blades rotate. The amount of interference depends on the strength of the scattered signal relative to the primary signal. This decreases with increasing distance between the receiver and the wind turbine, but is also affected by the position of the receiver relative to the TV transmitter and the wind turbine. As the wind direction changes, the blade may then reflect the television signal to some new receiver in the manner of a mirror being rotated. Interference may then occur at some habitations for only a fraction of the year when the wind is in a certain direction and specular reflection of the signal occurs. The problem is more severe in areas with an existing weak signal, or where the property is using an inadequate antenna, an incorrectly aligned aerial or where reception is weak due to the shadowing of the affected property by a hill. Unfortunately this is a typical case for a wind turbine installation. The interference which extends the greatest distance from the turbine occurs when the turbine is between the receiver and the transmitter. Here, a narrow pencil like zone can extend for a kilometre from the wind turbine, pointing away from the transmitter.

A number of methods can be used to improve reception. A high quality directional aerial can be installed or a low power "deflector" transmitter can provide a stronger, steady signal. Cable can be used to capture the signal from an aerial position not affected by the turbine.

There are two methods for forecasting the zone of interference around a wind turbine. One is by Senior and Sengupta (1978) and the other is by van Katz (1984). The method of Causebrook and Palmer (1982) assumes that field measurements have already been taken at the site. For Cornwall, turbines over a range of sizes with wooden blades and with full lightning protection were used to predict the radii of interference. The worst case criteria were entered, namely the highest frequency and the poorest receiver discrimination for habitations situated at the greatest distances from the transmitters. The predictions showed this zone to be approximately ten times the wind turbine's diameter in extent around the machine by the method of Senior and Sengupta and from thirteen to sixteen diameters for the method of van Katz. We had no means of deciding which method gave the more accurate figures, Senior's method did involve quite a lot of interpolation and this may have reduced its accuracy.

The result is that the separation zone for noise was greater than the separation zone for TV interference such that the latter is unlikely to be a major problem other than in areas of weak reception, or where the turbine is situated directly between the receiver and transmitter. Every wind turbine site which it is intended to develop will have to be checked on an individual basis.

4.4.4 Explosions Initiated By Radio Waves

Electromagnetic waves produced by radio frequency transmitters will induce electric currents in any conducting structure on which they impinge. The magnitude of the induced current depends on the shape and size of the structure relative to the wavelength of the signal and the strength of the electromagnetic field. When parts of the structure normally in contact are caused to separate or break, a spark may occur. If this happens where a potentially flammable or explosive atmosphere is present, a hazardous situation can occur.

Similarly, if radio waves are induced into a structure which is the firing circuit of an electro-explosive device, the current could inadvertently initiate its detonation.

British Standards 6656 and 6657 (1986) give guidance on the separation distances for a range of radio emission sources from tanks containing inflammables and from quarry and weapon stores. No information is contained therein on any effects which could arise from a reflected signal from a wind turbine. The more obvious locations in Cornwall and just over the Tamar are already protected from wind turbine installations for other reasons.

4.5 Radio Frequency Interference: Results

Prior to the radio frequency interference survey there were 2220 potential wind turbine sites. 709 were a potential hazard to radio services reducing the net total to 1511. In addition several hundred potential sites which were not enumerated in detail and were not included in our figure of 2220 were lost in the clay area. Wherever possible, sites were moved a few hundred yards to avoid separation zones, but the unavoidable loss of sites due to radio frequency interference still amounted to about 40% of the total. Radio masts and microwave links favour the same type of high, open topography best suited to wind energy. Given the rapid growth in microwave telecommunications the situation is likely to get worse each year.

4.6 Radio Frequency Interference: Conclusion

Radio frequency interference is a serious problem which eliminated about 40% of the Cornish wind energy resource and will continue to reduce the number of available sites in future years.

4.7 Radio Frequency Interference: Recommendation

There are heavy penalties for any errors in siting. The planning tools currently available are quite inadequate and work needs to be funded to prepare a suitably "bench marked" Radio Frequency Interference Siting Manual which can be used with confidence by wind engineers. The costs quoted by Bradford University and the ERA for field measurements at prospective turbine sites to search for frequencies with which a turbine might interfere is approximately £7000 per site. There is a case for the manual to include advice on these procedures. Perhaps the necessary equipment could be purchased and held by the Energy Technology Support Unit in conjunction with instrument hire companies for use by the wind engineering community.

Radio Frequency Interference References

ALNATT, J.W. & PROSSER, R.D. (1965)
"Subjective quality of television pictures impaired by long-delayed echoes." Procs IEE, Vol 112, No 3.

BRITISH BROADCASTING CORPORATION. (1986)
"BBC transmitting stations." BBC Engineering Information. London.

BRITISH STANDARDS INSTITUTE. (1986)
"Prevention of inadvertent ignition of flammable atmospheres by radio frequency radiation." BS6656.

BRITISH STANDARDS INSTITUTE. (1986)
"Prevention of inadvertent initiation of electro-explosive devices by radio-frequency radiation." BS 6657.

CAUSEBROOK, J.H., & PALMER, H.P. (1982)
"The reflection and scattering of television signals by the blades of large wind turbines." IBA, Winchester.

CCIR
Report 715/1, Geneva.

CHIGNELL, R.J. (1986)
"Recommended practices for wind turbine testing." 5: Electromagnetic Interference Preparatory Information. International Energy Agency and Electrical Research Association. Issue 1.

CHIGNELL, R.J. (1986)
"Electromagnetic interference from wind energy conversion systems - preliminary information." Procs: European Wind Energy Conference, ed. W.Palz, pp 583-6, Rome.

HALL, M.P.M. (1979)
"Effects of troposphere on radio communication." Peregrinus Ltd.

INDEPENDENT BROADCASTING AUTHORITY. (1987)
"Transmitting stations: Independent television and local radio." Winchester.

MANNING, P.T. (1983)
"Environmental impact of the use of large wind turbines." Wind Engineering, Vol 7, pp 1-11.

MIYAMOTO, D. T. & FORD, R.R. (1980)
"Wind turbine generator electromagnetic compatibility study." Kahuku, Oahu, Hawaii. 1843 Electronic Engineering Squadron, Hickam U.S. Air Force Base 15th Feb to 5th March.

MIYATOTO, D. T. & FORD, R.R. (1981)
"Wind turbine generator electromagnetic compatibility study." USAF, Hawaii, 23rd Feb to 13 March.

NEESEN, J.T,A. & OUDERLING, J.M.G.A. (1979)
"An inventory of conditions and requirements for the installation of large scale windmill networks with respect to their impact on telecommunication networks." Dr Neher Labs Report 454. October.

NEESSEN, J.T.A. & OUDERLING, J.M.G.A. (1981)
"Calculations on the scattering properties of wind energy conversion systems." PTT Report 475. 1981.

PERSHAGEN, B. (1981)
"Environmental and meteorological aspects of wind energy conversion systems." Final report. Task 1, International Energy Agency Report. NE 1981-25. N. Swedish Board For Energy Source Development.

ROBSON, A. (1983)
"Environmental aspects of large scale wind power systems." IEE Procs. Vol 130 Part A. December.

SENIOR, T.B.A., SENGUPTA, D. L., and FERRIS, J. E. (1977)
"TV and FM interference by windmills." Radiation Laboratory, University of Michigan Final report, Wind Systems Branch, Department of Energy, Washington DC.

SENIOR, T.B.A. & SENGUPTA, D. L. (1978)
"Wind turbine generator siting and TV reception handbook." Radiation Centre, University of Michigan. Published by US Department of Energy.

SENGUPTA, D.L. & SENIOR, T.B.A. (1979)
"Electromagnetic Interference To TV Reception Caused By Horizontal Axis Windmills." Procs IEE, Vol 67, No 8, pp 1133 to 1142.

SENGUPTA, D. L. & SENIOR, T. B. A. (1978)
"Electromagnetic interference by wind turbine generators." Radiation Laboratory, University of Michigan. Final Report No 2, Wind systems branch, Department of Energy, Washington DC.

SENGUPTA, D. L., SENIOR, T. B. A. & FERRIS, J. E. (1980)
"Television interference tests on block island." Radiation Laboratory, University of Michigan. Technical Report 3, Wind Systems Branch, Department of Energy, Washington DC.

SENGUPTA D. L., SENIOR, T. B. A. & FERRIS, J. E. (1981)
"Measurement of television interference caused by a vertical axis wind turbine." Radiation Laboratory Report 018291-2-T. University of Michigan.

SKOLNIK, M.I. (1961)
"An analysis of bistatic radar." IRE Transactions on Aerospace & Navigations Electronics.

WEBER, J. & STILLING, E. (1986)
"Electromagnetic interference from WECS." Danish PTT.

5. BLADE THROW

Abstract

In 1981 Eggwertz et al predicted the probability of a blade structural failure to be one in a million per annum per wind turbine. Since that time experience has shown that the probability of failure is very much greater than this. An historical perspective on wind turbine development indicates that the unsupported, cantilevered, blade emanating from aerospace design philosophies has been less successful than the more conservative, supported cantilever type which has built-in redundancy.

This safety issue appears to have been given too little attention both in terms of siting and the effective licensing of turbines.

The conclusions are that erection and maintenance operations and commissioning trials carry a high risk, frequent inspection is essential as is the need to reduce the risk of a "runaway" when the main supply of electricity to the turbine is disconnected since in these circumstances the blade or missile throw distances are greatest. If a missile throw occurs during normal operation, and not during a runaway, then the separation criteria determined from considerations of turbine noise will generally dictate that the nearest habitation is out of range.

It is recommended that research be directed at providing a self-excited, electrical braking load immediately on disconnection, that more redundancy should be built into the safety systems than has been typical of most medium sized machines, that the aerodynamic braking needs to be synergistic in operation and that normally rated high speed shaft disc brakes are no longer eligible as one of the two methods of rotor braking due to their ineffectiveness in runaway conditions.

5.1 Blade Throw: The Problem

Wind turbines can throw ice, rotor fastenings and particles, or even whole blades, for considerable distances. What is the probability of a person being hit by such a missile and does this possibility condition siting policy or machine design ? To answer these questions is the aim of this chapter.

5.2 Blade Throw: The Method

The theoretical predictions of blade throw were examined and then compared with the record of the last five years' experience.

5.3 Blade Throw: Work Done

The probability of a wind turbine shedding a blade, a blade fragment, or ice, and then throwing it a sufficient distance to hit neighbouring properties has been examined. The main findings were :

Eggwertz et al predicted that wind turbines built to the present design codes and with conservative component reliabilities could expect only one serious structural failure per 10,000 wind turbines operating for 100,000 hours. This corresponds to a failure rate of less than one in a million per year per turbine.

Macqueen et al accepted this probability level and devised programs (IMPACT and RISKIT) to predict maximum throw distances and the probabilities of impact per square metre of territory at various distances from the wind turbine.

The blade or blade fragment could be released at any azimuthal position of the blade. However, there is probably a slightly higher chance of release just after the blade passes through the vertically downwards position (6 to 7 o'clock) because here, the additional centrifugal load and tower shadow effects could combine to trigger a release. In this case the blade would be set free at, or near, the angle favouring the maximum throw distance. Other factors which help to determine blade throw distances are :

(a) The hub height of the wind turbine above the surrounding countryside and the physical size of the turbine only influence blade throw distances to a small degree;

(b) The position of the break along the blade. This affects the ratio of the area to the mass of the blade. A tip fragment, although released with a higher initial speed than a whole blade, will be rapidly slowed down by higher drag so may travel little further;

(c) The speed at which the projectile is released. This is the main determinant of blade throw distance. Two conditions can be considered :

(i) The blade, or part, is released at or below the normal operating rotational speed of the wind turbine or say 10% above this value as constrained by overspeed sensing and control. The maximum blade throw will then be a function of design tip speed :

Table 5.1 Maximum Blade Throw Distances
(To include ground affected by the scatter of fragments):

Tip Speed Ratio	Tipspeed Plus 10%	Turbine dia: / Tower Height: / Fragment Size:	15.0 m / 20.0 m / 1.5 m	40 m / 45 m / 8 m	60 m / 60 m / 10 m
4	40m/s	Blade	74.0 m	95m	50m
		Fragment	150.0	160	250
6	60m/s	Blade	113.0	120	100
		Fragment	221.0	247	320
8	80m/s	Blade	168.0	150	150
		Fragment	270.0	350	390
10	100m/s	Blade	228.0	170	195
		Fragment	303.0	425	460

(ii) In a runaway condition, rotors will quickly accelerate to a speed where total braking torque due to blade drag equals the total torque due to lift in which condition rotational speed should stabilise. Blade planform, blade pitch angle and twist will influence this speed, but from Macqueen et al (1983) and Hutter (1977) an upper limit of twice the design tipspeed can be adopted for most practical rotors. In any case, the ultimate tip speed will not exceed the speed of sound (330 m/s). Therefore, the final rotational speed achieved by the rotor in a runaway will vary with wind speed and design tipspeed :

Table 5.2 Runaway Blade Throw Distances

Design Tipspeed Ratio	Typical Design Tipspeed m/s	Runaway Speed m/s	Approximate	Maximum Blade Throw (Approximate)	Maximum Fragment Throw (Approximate)
			15m Dia.	140m	252m
4	36.6	73	40m Dia.	140	310
			60m Dia.	130	350
6	55	110	15m Dia.	270	320
			40m Dia.	175	450
			60m Dia.	200/261	490/530
8	73	146	15m Dia.	420	370
			40m Dia.	230	530
			60m Dia.	240	670
10	91	182	15m Dia.	600	420
			40m Dia.	300	555
			60m Dia.	280	750
Speed of Sound Maximum Conceivable distance of wreckage :				830	830

The above table has been compiled on the assumption that the blade or fragment will tumble in flight such that all the lift vectors reduce to nil for any one rotation and the drag is derived from the mean of all the attitudes achieved by the object in flight. However, Macqueen et al (1983) considered that the possibility of stable flight, could not be entirely ruled out. This would mean that the projectile flies like a javelin with a lift coefficient of say 0.8. The chances of this actually happening are extremely remote. For a 91 m diameter machine they gave ultimate stable flight blade throw distances of:

	Blade	Fragment
Fragment release speed of 110 m/s	391 m	841 m
340 m/s	1649 m	2245 m

The area weighted probabilities of impact per sq.m of land per throw at various distances from the tower were derived from the IMPACT program.

This shows that the highest risk of a strike occurs within about one and a half diameters of the tower and there is a secondary, lower peak near the limits of the blade throw range. Outside this zone, probabilities fall to less than one in a million per throw. This figure must be multiplied by 10 Exp -5 to account for the annual probability of a blade failure. When one makes an allowance for a blade sweeping over a larger area on impact than 1 sq.m., there is an overall predicted risk of the order of 10 Exp -7 for a blade, or 10 Exp -9 for a fragment. This compares to the U.K. risk of death by lighting of 10 Exp -7. The chances of being hit by a stable flight projectile are less than 10 Exp -7.

The above assumes that the target square metre of ground is occupied continuously by people throughout the year. This is a reasonable assumption for a building, but not otherwise.

These predictions were made in 1981-3. This was before the substantial expansion of wind energy in the United States and Denmark. How has the experience of the past five years matched these predictions? From the list of sources given at the end of the chapter, table 5.3 was compiled. This is likely to under-report the situation because not all incidents will have been recorded in the wind engineering press.

Table 5.3
Recorded Incidence Of Blade Or Fragment Throw And Blade Structural Damage

Machine	Dia.	Capacity	Date of incidents	Blade Material	Position of break	Throw distance	Notes
	m	kw					
Carter	9.76	25	1981-3	G.R.P.	Root	Various, mostly close to tower	Livingston Montana: 5 machines rebladed - yaw error followed by blade coning and then striking tower.
		20					Tehachapi Blades hit towers on 11 machines.
	19.8	200	1983-4				San Gorgonio: 2 Blades hit tower on 2 machines. 15 blades were 'lost'. Subsequently 12 sets of blades lost - designers said to have overlooked shear loads, since rectified.
Alcoa (V.A.) San Gorgonio	25	500	3 April 1981	Aluminium Alloy	Total Destruction	About 120 m.	Overspeed on inaugural rotation due to software programmer's error in control equipment.
W.T.G. Mt.Equinox, Vermont	24.4	200	25.12.83		Blade root connection	Near Tower	Structural failure
		200	31.12.83	Steel	Rotor Separated from low speed shaft	" "	Possible failure of low speed gearbox shaft
W.T.G./Howden CEGB, Carmarthen Bay	24.4	200					Machine taken out of service when cracks discovered in blade root area.
Fayette Altamont	16	75	1983	G.R.P.	Root		Blade losses reported. Subsequently 2% annum of all operating machines quoted as loss rate for blades.
Polenko	15	60					Numerous strut failures on early machines.
Climax water-pumping windmills 1980s following		<1		Steel	Usually root		Waterpumping turbines are listed on the 1:25,000 map. 41 were visited, 38 of which had lost one or more blades.
W.E.G Orkney	20	250		Steel	Tip junction		Damage to a blade tip fairing.
Grylls/Long Exeter V.Axis	12						Insufficient electrical load for machine, therefore operation terminated.

Machine	Dia.	Capacity	Date of incidents	Blade Material	Position of break	Throw distance	Notes
	m	kw					
Mehrkham	12	45	1979-82				Designer/Operator killed ir runaway by being thrown fron tower. 50 machines built, many lost blades - all were eventually scrapped.
E.S.I. U.S.A	16.46	50	1982-3	Wood Epoxy	Yaw bearing	Close to Tower	1.Prototype: severely corrodec yaw bearing failed; entire nacelle fell to ground during normal operations.
					Yaw bearing		2.Production Model: Failure of tip brakes to fully deploy ir overspeed caused 'systen destruction'.
					Yaw bearing		3.Production Model: Entire tip brake mechanism thrown off during normal operation. Machine subsequently overspeed due tc loss of grid, mechanical brakes failed, entire machine fell from tower. Quality assurance during manufacture implicated
Aerowatt	18	125			Root	?	
Bendex	50	1300	May 1983	Wood Epoxy			Covering material of one blade thrown off.
MOD O	38	100		Aluminium Alloy	Concern re. root	N.A.	Original aluminium alloy blades replaced after limited operatior due to fatigue damage.
John Brown Hill, Orkney						N.A.	Machine dismantled unsatisfactory rotor operation.
Saab-Scania Sweden	18	60	1977		Not reported	N.A.	Ice, about 5mm thick, deposited on blade during shutdown, was thrown about 20m from tower as blade flexed during run-up tc power. Observed twice 1977-78. N.B. - downwind rotor.
Nibe A	40	630		G.R.P. and Steel	Root of outer section	N.A.	Limited operation due to blade root fatigue damage.
Growian W.Germany	100	3000					Dismantled due to unsatisfactory operation.
M.B.B. W.Germany	50			G.R.E.			Blades proved to be too flexible, so were reduced in length.
Rutherford Appleton Laboratory	5						Operation limited due tc torsional oscillation of cross member.

Machine	Dia. m	Capacity kw	Date of incidents	Blade Material	Position of break	Throw distance	Notes
G. Palmer-Putnam Grandpa's Knot, Vermont	53.3	1.25MW	26.3.45	Stainless Steel	Root	250m From 7 o'clock position	On load at 50 - 475 kW. Blade was thrown 250 yards during 28 rpm, 78 m/s tip speed operation. Contributory causes: stress rise at root due to design modifications and notching. Fatigue when left for 2 years in stationary position, but oscillating in wind. Corrosion. The throw distance was above Sorensen's forecast of 170 m. Hill slope may have contributed to the extra distance recorded.
Tvind Denmark	60	2000		G.R.P			Severe flap resonance - speed of rotation and power output limited.
Elliott Isle of Man 1960	15	100	about	Aluminium			Blades damaged when yaw pintle of bearing failed and allowed blades to hit tower. Machine then scrapped.
U.S.Windpower	17.07	50	1983	G.R.P.	Root	Entire rotors less than 1 D from tower base.	Over 300 out of 585 machines reported to have equipment problems. Pile of 40 broken blades reported. Overspeed problems contributed to failures.
D.A.F. Indal V.A.		500		Extruded Alloy		80m	Ran away after unexpected self start during maintenance stoppage Machine destroyed.

Machine	Dia. m	Capacity kW	Date of incidents	Blade Material	Position of break	Throw distance	Notes
Howden Palm Springs SCE 1 off	26	330		Wood Epoxy Saturation of Khaya	Root		Lost all three blades during normal operation in 18-31 m/s winds due to faulty bonding of root section. Fine cracks had appeared in blades.
Altamont Pass 75 off	31	330	June 86	"	Blade root		3 machines affected - 1 blade thrown.
					Tip root	c. 350 m	1 tip thrown.
				"	Tip root		1 tip thrown.
10 off	15	60					Specification of stud material and incorrectly installed studs in root were reported as the cause. All machines then shut down for retrofitting of blades. Also fine cracks observed in blades.
Altamont Pass	33	330	1988	"	Root bolts.		1 Blade lost after retrofitting new blades, due to operator error.
Orkney	22	300	1986 or 87		Tip		Hit concrete at base of tower
Rutherford Appleton	15	55	1987				Water ingress into blade caused replacement.
[illegible]ECS Holland	25	300	1983	G.R.P.	Severe blade damage	N.A.	Runaway due to wrongly programmed controller overruling safety shutdown procedures, led to 150 rpm.
[illegible]erway Holland Multiple H.A. [illegible]ors on one [illegible]er.	15	6*75 kW	1986		Rotor damaged		Blade damage by high winds during erection.
Windmatic St Helena			c 1984	Wood/ G.R.P.	Machine destroyed	c. 300 m	Runaway off load.
Windkrafte Zentrale's Windrose [illegible]hine, W. Germany	6.4	10	1974-1981		Tower base and blade root		260 produced, 234 in Denmark. Defective design. 19 totally destroyed with tower falling over, 130 damaged in a single storm in Nov. 1981. Only 36 left operating in 1985.
Wind Power Systems Tehachapi [illegible] machines							Hub incorrectly designed.

Machine	Dia.	Capacity	Date of incidents	Blade Material	Position of break	Throw distance	Notes
	m	kw					
Nordtank Tehachapi	18		Jan.85			1. Turbine fell over 2.Nacelle fell off tower. 3.Blade lost	50 m/s winds, 20 runaways with damage. Inadequate maintenance cited as cause.
A.S.E.A. Christchurch, N.Z.	10	40	1987				Entire turbine collapsed. Error made in tower design.
Flowind V.A.	17	125	1986	Aluminium Alloy	Root	N.A.	Blade stress cracks. All models retro-fitted with improvements.
Wincon Denmark	18	99	1987	G.R.P.	Entire nacelle fell to ground	10m Nacelle. Debris from blades: 250m	Brake parachutes failed to control runaway. Said to be 300 r.p.m. (?) No injuries.
Alternegy Blades	12-25m	55-250kW	1984	G.R.P.	Root Tip	Various	Primary blade supplier to industry 1982-1987. Total blades built probably exceed 10,000. None expected to survive 5 years of operation. Hutter root problems. Poor quality control, material shrinkage, thermal stressing.
Stork Blades	19m	100kW	1987	G.R.P.	Root	?	Problems reported with Hutter root design.

5.4 Blade Throw : Result: Probability Of A Throw

The evidence of the last six years shows that Eggwertz's predicted throw rate of 1 in 10 Exponent -5 per annum is grossly optimistic. Missile throws have not been recorded in sufficient detail to give reliable figures. However, there are a very large percentage of Danish glassfibre blades in the total sample and these are not expected to exceed a life of approximately five years. Well over 10,000 of these blades have been built and account for over a sixth of all wind turbine blades currently in use. Therefore, the probability of problems arising with blades or tips is very much greater than Eggwertz predicted.

5.5 Blade Throw: Conclusions

1. A very long time is needed before any design can be confirmed as satisfactory. Structural integrity is only as good as the weakest of seven links in a chain made from considerations of:
   1. stiffness criteria
   2. material properties
   3. stress analysis
   4. loads and environment
   5. component analysis
   6. structural design allowables
   7. the quality control of materials and fabrication. Bruhn (1973).

The elements which account for most blade failures are materials, component analysis, quality assurance and thermal/humidity effects.

There have been persistent problems at the interface between: the stiff, cast steel or cast iron blade hub which moves primarily due to thermal effects, and polyester glassfibre's tendency to shrinkage. For wood epoxy roots any thermal movement, particularly on the largest diameter hubs, meets the dimensional instability of wood which normally varies slowly with time, but does so quickly if superficial damage allows an ingress path for humidity.

Wholly cantilevered blades with innovative roots, and no built-in redundancy which have emanated from an advanced, aerospace design philosophy have faired less well than a more conservative approach with built-in structural redundancy. The latter design is less material efficient, more expensive to build and can be aesthetically less pleasing. However this type of design has operated successfully in numerous machines for well over ten years. Witness the designs of Schmidt 1940-1954 (stopped operating due to change from DC to AC), Juul 1957-, Tancred 1976-, and early machines from Windmatic and Vestas which their makers say continue to operate satisfactorily.

2. Erection and maintenance operations have been shown to carry a high degree of risk. This goes some way in explaining both the difficulty of getting insurance cover for these tasks in the UK, and the very high rates which are charged when it is made available.

3. Frequent machine inspection is essential.

4. Blade damage and the greatest blade throw distances arise during runaways. These largely happen because of a loss of electrical torque when the connection to the main supply is cut. Rapid acceleration usually means that high speed shaft disc brake peripheral speeds immediately rise beyond the brake pad temperature limit. The movement of aerodynamic surfaces typically can take ten seconds to bring rotational speed back to the design level, before which excessive loads can occur.

5.6 Blade Throw: Recommendations

1. There is a higher probability of a blade, blade fragments, or ice hitting the ground close to the tower. Therefore, for 30% beyond a distance from the tower equal to one blade length and the hub height, there should be no buildings or activities which involve other than passage by the machine operators and the leasor of the site. There should be no road, railway or frequently used right of way within this zone. There is only a very, very remote probability of a blade fragment gliding in flight to a distance of 2.2km. There may be a case for not locating a wind turbine less than this distance from a town since this would present a large target area but further research may show this to be over-conservative.

2. Blade throw distances for medium size machines which do not run away are typically less than the distance to the nearest habitation, if this latter distance is determined on noise grounds. However for a runaway, an ultimate missile throw of about 800m is possible. This exceeds the greatest habitation separation distance in Cornwall. Machines need to be equipped with electrical braking which can be self-excited immediately on mains failure in order to prevent a runaway.

In addition, there needs to be more redundancy built into the failsafe procedures should a runaway occur. An example would be that the first level of rotor speed rise is sensed at the generator shaft which is set for plus 8%. The slow speed main shaft is set for plus 10%. This duplicates the generator sensor and would provide warning if the gearbox failed. The blade tips are held against the end of the mainblade by hydraulic pressure and any loss of the mains supply will release a solenoid which in turn allows the tips to travel outwards under the action of centrifugal force. The tip shaft has a cam running in a helix which turns the tip to act as an air brake. Also, the hinge of the tip is behind the aerodynamic centre so that the pressure of the wind aids the turning motion. Should the solenoid valve fail to vent oil, due to, say, some foreign matter in the port, then the pressure in the hydraulic circuit will rise as the centrifugal force continues to act on the tips until a set level is reached which will open another valve to vent the fluid. As a final backstop, there is a shear plate in the tip mechanism which is designed to fail at 170% of full speed.

In this way the failsafe mechanism is synergistic in that the forces causing the rise in speed also directly act to brake the rotor. The majority of designs which ran away did not have this level of redundancy, nor this synergistic approach. Current safety regulations allow the high speed shaft disc brakes to act as one of the two ways to bring the machine to a halt. These are inadequate when needed in a runaway. Synergistic deployment of a drag device needs to be specified in its place, and self excited electrical braking should be installed to prevent a runaway when the grid connection is cut.

Blade Throw References

EGGWERTZ, S., CARLSSON, I., GUSTAFFSON, A., LINDE, M., LUNDEMO, C., MONTGOMERIE, B., THOR, S.E. (1981)
"Safety of wind energy conversion systems with horizontal axis." Technical Note HU-2229, Aeronautical Research Institute, Bromma, Sweden.

MONTGOMERIE, B. (1982)
"Horizontal axis wind turbine blade failure, blade fragment six degree of freedom trajectory." Site risk level prediction, Wind Energy Systems Vol 2, pp 389, BHRA Cranfield.

MACQUEEN, J.F., AINSLIE J.F., MILBORROW, D.J., TURNER, D.M., SWIFT HOOK, D.T. (1983)
"Risk associated with wind turbine blade failures." I.E.E. Proceedings, Vol. 130, Pt A., No.9, December.

HUTTER, ULRICH, (1977)
"Optimum wind energy conversion systems." Annual Review of Fluid Mechanics, 9, 399-419.

WEBER, WOLFGANG, (1975)
"Die optimale auslegung rotierender flugel fur horizontale windenergiekonverter." Z.Flugwiss. Haft 12.

SORENSON, J.M., (1984)
"Prediction of site risk levels associated with failures of wind turbine blades." European Wind Energy Conference, Hamburg, 22-26 October.

BRUHN., E.F., (1973)
"Analysis and design of flight vehicle structures." Tristate Offset Company U.S.A.

Blade Throw Sources

Wind Energy Report	P.O. Box No.14WR, Rockville Centre, N.Y. 11571 1981-1983
Windirections	Newsletter of British and European Wind Energy Association, 1980-1987.
Windpower Monthly	Forlaget Vistoft Aps., Vrinnes Hoved, 8420 Knebel, Denmark, Jan. 1985-1987.
Press cuttings	1976-1987.
Wind Power Stations 1983 Survey	Strategics Unlimited, published by EPRI 1984.
Wind Power Stations 1984 Survey	Strategics Unlimited, published by EPRI 1985.
Wind Power Station : Final 1985 Performance and Reliability	EPRI AP-4639 Project 1996-2. Report prepared by R. Lynette & Assocs. Inc., Redmond, Washington. June 1986.
Wind Power Station : Performance and Reliability	R. Lynette Associates, 1986 published by EPRI 1987.
G. Courage	Risk Analysis of WECS - Insurance Aspects, European Wind Energy Conference Procs., pp 844-848, Hamburg 1984.
Beuriskens, H.J.M., Elliot, G., Jensen, CEC P.H., Molly, J.P., Schott, T., de Wilde, L.	Safety of small and medium wind turbines, Contract Report for CEC., October 1986.

6. DOMINATION

6.1 Domination: The Problem

Remarks made to wind turbine operators in the UK and Denmark suggested that some people may feel physically threatened by the near presence of a wind turbine. One person complained that "it looks right in through my windows" and several people have said they feel dominated by the new 2MW machine near Esbjerg in Denmark. (Windpower Monthly, 1988). At Treculliacks and Ilfracombe the height of the wind turbines above nearby houses is increased by the hills on which they stand so that machines of moderate size can also dominate surrounding properties.

6.2 Domination: The Aim

The aim was to see how turbines should be sited to avoid this problem.

6.3 Domination: The Method

In the public perception survey each respondent was asked if they could see the machine from their house or garden, whether they noticed if it was working and if they thought the turbine was positioned too close, about right, or too far away.

6.4 Domination: Results

The results were plotted with the angle of elevation above the property of the highest point of the machine as a function of distance away from the turbine. If this angle was more than ten degrees domination became an issue. It should be emphasised that in most cases the turbine was situated so that it was visible only from a little used window at the side or back of the property. For turbines which were so insensitively placed as to occupy the cherished view, or main outlook from the house windows, or from that area of the habitation's curtilage where most occupation takes place, it is anticipated that the separation distance would need to be greater. There is insufficient information on this point, but for the purposes of this survey a provisional figure of four degrees angle of elevation is used. As the ten degrees angle only applies to properties where the machine can be seen from a little used vantage point, this is not a restrictive condition because the majority of houses turn their backs on the hillside and look out towards the lower ground; so the hilltop turbine is often masked by the brow of the hill, trees, fences or outbuildings and little resource will be lost by avoiding properties not so aligned.

6.5 Domination: Conclusion

When the turbine is viewed from the non-cherished outlook from a habitation, the angle subtended at the habitation between the top of the rotor disc and the horizontal should be less than 10 degrees. For machines placed in the cherished viewpoint from a habitation the angle would need to be less. Insufficient information is available to determine the correct separation distance in these circumstances and for this study a provisional figure of four degrees is used.

7. FLICKER

Abstract

Wind turbine rotors cast shadows which appear as flicker to an observer. This is not likely to be a problem for surrounding habitations as the separation distances required on the grounds of noise will exceed those resulting from flicker.

7.1 Flicker: The Problem

Shadows cast from rotating wind turbine blades appear as flicker to an observer. If a wind turbine is sited close to a building so that shadows are cast onto the windows, this can annoy the occupants. This has been reported at Riso and at a site in Holland. The effect is of short duration as the sun soon moves the shadows elsewhere and they will only affect a particular spot at certain times of the year.

The range of frequencies which cause annoyance is from about 2.5hz to 40 hz. It is believed that flicker can cause dizziness and disorientation. A frequency of between 2.5 hz and 3 hz can trigger epileptic seizures for some 5% of those who are susceptible to them. About 2% of the population are epileptics. Higher frequencies of 5 hz to 15 hz can even cause convulsions. This frequency is not likely to arise with the type of wind turbines contemplated for Cornwall. Technicians should not be employed on wind turbines if they suffer from epilepsy.

7.2 Flicker: The Aim

The aim was to see how flicker may affect the siting of wind turbines.

7.3 Flicker: Method and Results

The maximum length of time per day that flicker is likely to affect positions around wind turbines was calculated for Cornwall's mid-latitude:

Table 7.1 Flicker Caused By Wind Turbines.

At two diameters from the machine: Direction From Machine	Up to one hour of flicker per day: Flicker Months
North	February and October
40 and 320 degrees	Mid Feb to Late March
80 and 280	April to mid May Mid July to late August
120 and 240	Nil
At ten diameters from the machine	
North	Nil
40 and 320 degrees.	Late November to mid January.
80 and 280	One week after each equinox
120 and 240	Late May to late July.

7.4 Flicker: Conclusion

The separation distance required for noise exceeds these distances. Flicker is not considered to be a siting problem.

Flicker References

VERKUISLEN E., WESTRA CA., (1984) "Shadow hindrance by wind turbines." pp 356-361 *Procs of European Wind Energy Conference*, Hamburg 22 - 26 October.

8. BIRD STRIKES

Abstract

There is a shortage of information on this subject. Figures from California suggest that one bird may be killed each year per three hundred turbines installed and for this reason it is recommended that turbines should not yet be erected in areas where there is a particularly dense bird population.

8.1 Bird Strikes: The Problem

The small wind generator on Godrevy Island in St Ives Bay was reported to have killed a large number of seagulls in the mid 1970's.(Private communication with Trinity House). In California, the United States Fish and Wildlife Service has reported bird deaths in the Californian windfarms at the rate of one death per three hundred turbines per annum. (Windpower Monthly, May and June 1988). Threequarters of these deaths arose from collisions with rotors and the rest from electrocution on, or near, windfarm overhead conductors. What appears to have happened on Godrevy is that a small rotor with a high speed of rotation and narrow blades was not easily seen by birds crowding onto the island - hence the deaths. Larger blades moving at a lower tipspeed appear to be visible to birds in normal weather conditions and it may be significant that most U.S. deaths have been reported near rotors with the fastest moving, slimmest blades. There is a shortage of information on this subject. Without systematic research, with no formal reporting procedure, and with the probability that dead birds would be carried off by other predators such as badgers and foxes it is possible that the number of deaths has been under reported.

Larks regularly ascend and descend close to the author's turbine, and swallows, buzzards and jackdaws fly close to the rotor without colliding with it. The site is checked every day the turbine runs. One dead jackdaw was found at a distance of 45m from the machine during the last ten months of continuous operation. The bird had no signs of physical injury and it is not known if it was killed in collision with the blades.

8.2 Bird Strikes: Recommendations

1. More research is required.
2. Meanwhile turbines should not be sited in areas with very dense bird populations.
3. Windfarm electrical transmission systems should be cabled underground.

9. WIND TURBINE ENVIRONMENTAL POLARS

9.1 Wind Turbine Environmental Polars: Results

Non-dimensional, composite polars for wind turbines in the Cornwall area have three concentric zones:

1. Inner Zone of Two Diameters from the Machine.

   Here the effects of missile throw, infrasound, flicker and domination are most severe and it is proposed that this zone does not encompass a road, path or an area which people normally frequent. There will be no habitations in this zone and preferably the only buildings, if any, are those occupied by the wind turbine operator. This area can continue to be used for agricultural operations by the leasor in the normal way, but the longer dwell times common to horticultural field operations may need to be avoided.

2. Outer Zone

   This is defined as the area within which the turbine can be heard downwind in normal atmospheric and operating conditions. Here there will be no habitations.

3. Far Zone

   This is defined by the maximum distance which a blade or blade fragment could glide, and within which there will be no towns or large areas covered with habitations. Further research may show that the probability of blade impact is so remote that this zone can be disregarded.

9.2 Wind Turbine Environmental Polars: Conclusion

The definition of these polars concludes the work of the first nine Chapters which establishes the ground rules for measuring the resource in Cornwall, before manipulating this data to find how topography and settlement patterns influence wind turbine design in maximising this resource.

Before proceeding to filter out the uneconomic sites by considering capital costs and income to the machines, the human response to wind energy development is considered and used to further condition our requirements for micrositing, and to see how the public's reaction may further influence wind energy development.

10. THE PUBLIC'S PERCEPTION OF WIND TURBINES

Abstract

The idea of an energy source with free fuel has a powerful attraction for most people.

Public reaction was assessed for two groups: those who have not, and those who have, been adversely affected in their homes by a wind turbine. For the first group the majority view was:

More than 4/5ths wanted to see the renewables developed.

About three quarters wanted to see no increase in the size of the nuclear industry and wanted the coal industry to continue to supply its existing share of the electricity generating mix.

In Cornwall, wind and geothermal were most often cited as the renewables on which to concentrate development. The main advantage cited for wind was its lack of pollution, its inexhaustibility and its safety.

The main disadvantage was the large number of turbines needed to equal the output of a conventional power station, as well as its unpredictability since the wind does not always blow.

Noise was considered to be the prime environmental disadvantage.

Although there was some resistance to seeing wind turbines in Areas of Outstanding Natural Beauty, people generally accepted the idea of wind turbines in the landscape, on hills, on ridges and near the coasts. Their visual intrusion was not a very significant factor.

However, administrators, politicians and the media often claimed that people would object on the grounds of visual impact, and used this as an argument for not considering wind energy. Smaller numbers of large turbines versus larger numbers of small turbines, turbines in clusters or single machines, what colour they should be, and at what speed they should rotate, evinced no clear preferences.

There was resistance to any grouping of wind turbines which resulted in a feeling of clutter in the landscape. There was preference for all the turbines in one group to be of the same colour and design, and for them all to rotate at the same speed. There was a preference for wind

turbines which most looked like the traditional corn grinding windmills, and resistance to unfamiliar designs. Solid shapes were preferred to skeletal shapes even though the latter presented less surface area to the viewer.

Turbines are expected to work all of the time and negative reactions result when they fail to do so. Wind turbines were thought to be expensive, difficult to develop, unreliable and uneconomic in operation.

Nevertheless, 59% of the people living near the author's wind turbine showed an interest in investing in it in order to reduce their electricity bills.

The planning procedures were considered inadequate in explaining to people what was involved in building a wind turbine. People reacted against manufacturers who were in any way condescending in their attitude to the public, or who obfuscated technical issues.

There was a very low level of understanding about how a wind turbine works and its role on an electrical distribution system with a mix of generation sources. Some of the negative attitudes towards wind arose from these misunderstandings.

About half of the people wanted more information about the subject.

Television interference, flicker from lights due to switching at the turbine, the disturbance of wildlife, the provision of employment were all considered to be of negligible importance. Landowners were generally agreeable to leasing small plots of their land for wind turbines.

The above response was typical for people living within sight of a turbine and who did not feel disadvantaged by it, or from people who had no knowledge or experience of wind energy. However, if people felt adversely affected in their homes, either because the angle of inclination above the horizontal to the top of the rotor exceeded about 10 degrees and/or if they were subject to turbine noise, then 4/5ths support for wind energy changed to 4/5ths antagonism. This was sufficiently hostile to create regional publicity and petitions. News of bad experiences sensitised District Councils to the noise issue and in order to avoid having to make detailed engineering considerations they have offered temporary planning consents for wind turbines.

10.1 The Public's Perception Of Wind Turbines: The Problem

If wind is to make a significant contribution to Cornwall's energy demand, then substantial numbers of wind turbines will need to be deployed either as single installations or in clusters of machines. Whereas, say, a coal-fired power station may have well over 10MW of installed capacity per property directly affected by its construction, wind turbines or a windfarm will usually have less than 0.5MW installed per property affected and it is difficult to imagine a significant resource being deployed without a high degree of public consent. This single issue will have a more dramatic effect than any other on the ultimate contribution made by wind energy and it is the purpose of this chapter to assess the public's reaction to wind turbines in the countryside, and from the experience to date to list guidelines which would facilitate their introduction.

10.2 The Public's Perception Of Wind Turbines: The Aim

The aim was to assess the public's reaction to wind turbines and to devise siting standards which met their aspirations.

10.3 The Public's Perception Of Wind Turbines: The Method

The literature was searched for surveys of public opinion. This information, together with responses to the author's machine at Treculliacks, and the subjective experience of other turbine operators in the UK, was used to compile a list of questions. Another literature search was carried out to see how these questions should be framed to avoid biasing the results. Martin Varley, a final year student at the University of East Anglia, then conducted interviews with people living closest to the following machines :

Site	Machine	Capacity	Manufacturer	Installed
Treculliacks, Constantine, Falmouth.	17.5m dia 3 bladed	145kW	Windpower & Co(UK)Ltd	April 86
Slade Farm, Ilfracombe, N. Devon.	25m dia 3 bladed Upwind	200kW	Wind Energy Group,M'sex.	Dec 1985
Lundy.	14.55m dia 3 bladed	55kW	Windmatic and NEI.	1984
Burger Hill, Orkney.	20m dia 2 bladed	250kW	WEG.	Dec 1983
	22m dia 3 bladed	300kW	Howden Glasgow.	Nov 1983
	60m dia 2 bladed	3000kW	WEG.	Autumn 1987.

The 60m machine had not rotated at the time of the survey.

These results were then analysed and compared with the literature in order to contribute towards sensitive siting standards for this survey and for the planning of future installations in Cornwall.

10.4 The Public's Perception Of Wind Turbines: Work Done And Results

10.4.1 A Review Of The Literature

Attitudes Towards The Use Of The Renewables And Existing Sources Of Energy

Ferber (1977) found that there was 4 to 1 support for the renewables over coal and nuclear power. He carried out a survey of 300 people in each of six different areas of the USA in 1976 and reported a 75% preference for hydro and wind over coal, even if the renewable sources would have cost the interviewee a 10% price increment. 50% support for the renewables was retained with a 25% price increase. Strong opposition was expressed to the idea of energy rationing.

Inga Carlman (1982 and 1984) carried out surveys with people in each of three areas of Sweden during 1979/80 and again in 1983/4. One area surrounded the 3MW Maglarp turbine, another the 2MW Nasudden machine, and a third area was a control zone where the inhabitants had no experience of wind energy developments. Her findings substantiated those of Ferber in that 86% of those questioned wanted hydro to replace oil after the year 2010 and 81% also wanted to use wind for this purpose. Coal was favoured by 11% and nuclear by 33% of those interviewed. Carlman's respondents ranked energy sources in terms of the least harm to the environment thus:

Wind	76%
Hydro	54%
Solar	37%
Nuclear	13%
Wood	7%
Heat pump	5%
Soil heat	5%
Geothermal	3%
Gas	2%

(In reply to this question respondents could name one or more energy sources of their own choice)

Attitudes To The Use Of Wind As An Energy Source

(Interviews conducted with people who had no experience of wind turbines.)

Again, high acceptability is reported. Wolsink (1986) interviewed four groups each in a different area of Holland during 1985 and Ferber (1977) and Carlman (1982) addressed this question in their surveys. Overall, an 80% acceptance of wind energy is reported. The main advantages cited are: "It is free" - or at least the fuel is. This is mentioned by all commentators. THE IDEA OF GETTING A FREE INCOME FROM AN INEXHAUSTIBLE SOURCE HAS A DEEPSEATED AND POWERFUL ATTRACTION FOR MANY PEOPLE. Other advantages cited were:

Lack of pollution	All interviewees.
Safe and natural source of energy	" "
Domestic availability	Carlman, Ferber.
Conservation of fossil fuels.	Wolsink, Carlman
Gives diversity of energy supply.	Carlman.

However, doubts were expressed about the perceived ability of wind to "deliver the goods" on account of:

Unpredictability

What happens when the wind does not blow? Respondents perceived wind as the sole energy source on which we might have to rely, and as this was clearly impractical they tended to dismiss wind as a possibility.

Unreliability

Many prototypes and a high proportion of the turbines in the Californian windfarms have been idle for very long periods so interviewees believed the technology to be unreliable.

Not Economic

Would Spoil The Scenery

Ranked as the fourth difficulty by Thayer's respondents Thayer (1986) and ranked low by Carlman's; but seen as the prime disadvantage in Wolsink's survey. This difference may be attributed to the relatively low population densities of Sweden and the USA where open spaces are not yet considered to be such a valuable resource they are in the Netherlands. On the other hand, a petition organised by the Community Council on Shetland at the news of Howden's proposal to build a 750kW, 45m diameter machine on Susetter Hill raised 81 signatures and visual intrusion was placed top of the list.

Interference With Birds, TV etc

Considered to be minor impediments by all respondents.

Noise

This was not an issue in areas where no serious problems had occurred, but news of bad experiences from the Maglarp machine and the one at Ilfracombe quickly sensitised the public and the administrators. The result was that three subsequent planning consents in the West Country were made on a temporary basis only pending satisfactory performance of the machines in this and other respects. Noise was mentioned as a potential hindrance to wind energy by Carlman's second survey and by the petitioners of the Susetter Hill machine despite the fact that the latter is over 1000m from any habitation. Noise is the single feature which has attracted most attention and comment from visitors to Windpower's machine. In this case, the response has been favourable in that visitors came expecting the machine to be noisy and commented when they found that it was not. This is hardly a fair test since the machine is heard immediately after being exposed to a high noise level in a car. A more comprehensive reaction can be gauged from people who live near the machine.

Wolsink and Thayer made the point that public opinion is, in principle, very favourable towards wind energy, but all interviewers found a very low level of knowledge about wind energy in general and an almost complete ignorance of how wind turbines actually work in detail. As such, their attitudes and opinions are unstable. Bad experiences or news of them destroys the public's predisposition in favour of wind. As Thayer put it "Wind is innocent until proved guilty", unlike nuclear plant around which a commentator found that people considered the technology to be suspect until proved innocent by long periods without serious incident.

The Type Of Countryside Believed To Be Suitable For Wind Turbines

Carlman and Ferber report a willingness among their interviewees to see wind turbines erected both on the coast and in scenic areas. Wolsink's respondents believed that most scenic areas should be kept clear of all structures. All reported a preference for wind turbines to be sited in "big country" i.e. open landscapes, high plains with broad vistas, thin settlement and distant views, which could more easily absorb wind turbines than closely settled, quickly modulating relief, where large machines would be out of scale with the surroundings which they would dominate. For example, the countryside between Cubert and Newlyn East would have been preferred to, say, the countryside between Truro and Penryn.

Siting on the shoreline itself has been accepted in Denmark where the idea of viewing the machine against the wide horizon of the sea was cited as an advantage. Here the scale of the sea and the turbines was considered compatible and, ipso facto, the land area from which the machine could be seen was only half that of a turbine situated inland. Permission to locate turbines near the Danish coast was refused, not for reasons of landscape, but for fears of birds colliding with the machines in a nesting area with a higher than average bird population Rasmussen (1986). Carlman and Ferber's respondents said that machines should be situated in areas where the winds were strongest and the economics would be best, even though these may also be scenic areas.

Arkesteijn (1984) proposed that turbines should be sited on the outskirts of built-up areas and near industrial estates. He proposed that they be positioned in a way which responds to the underlying structure of the rural landscape, in rows along linear features like roads, harbours, on piers, or canals. He favoured sites in a man made landscape in preference to areas where man's influence is negligible.

Views On Machine Design: Shape

Only Ferber carried out systematic tests. He showed his respondents pictures of six different types of machine. The following ranking emerged:

1. Traditional four bladed Dutch corn grinding windmill on wide, slightly tapered tower, i.e. the windmill familiar from pictures by Rembrandt to van Gogh.
2. Modern horizontal axis rotor mounted on Dutch tower.
3. Modern horizontal axis rotor mounted on columnar tower.
4. Modern horizontal axis rotor mounted on lattice tower.
5. Darrieus type vertical axis machine.
6. Gyromill.

There was a four to one preference for the traditional Dutch windmill type over option 4, and a 3 to 1 preference over option 3. The vertical axis machine ranked equally with the lattice tower design. Unfamiliar and skeletal shapes were not liked whereas solid and familiar shapes were.

Reports of visitors' reactions to nineteenth century English corn grinding mills said that the fantail's rotation was of more interest than that of the main rotor. Wailes (1949). The main blades rotated at a more or less a constant rate. The fantails would first rotate in one direction and then in another at varying speeds and rates of acceleration punctuated by periods of rest. This held the observer's attention and interest and has also been the case at the author's machine.

: Rotational Speed of Blades

Thayer reports a preference for the more slowly rotating types even though these tend to be larger machines. This reaction was expected at Treculliacks but visitors have found it very difficult to discern the difference between 38 to 59rpm. The idea that the turbine should rotate more slowly in a gentle breeze in sympathy with the relative calm of the countryside, and to rotate at full speed in a strong wind when the motion of the trees bushes and clouds gives a feeling of bustle and hurry to the landscape, was not mentioned by any visitors.

Miller (1987) noted a preference for three blades which give an even sense of rotation as opposed to two blades which appear to flick between vertical and horizontal positions when one blade is momentarily lost to view as it is masked by the tower.

: Colour

There has been no systematic treatment of this issue. In the Altamont the majority of machines are painted white and stand out strongly against the dark green hills. The result has been that many of Thayer's correspondents asked for a neutral colour scheme and objected to this degree of contrast. The City of Palm Springs brought a lawsuit against the Bureau of Land Management and the operators of the windfarms at San Gorgonio, which are situated in view of the city, on the grounds that the windfarms "threatened the visitors' aesthetic experience and the city's tourist potential" In an out-of-court settlement the operators agreed to repaint the blades of the machines in a non-reflective off-white colour and to remove non-operational wind turbines. WP1 has a light grey rotor and nacelle with a galvanised tower. Some visitors have said they would like a brighter, more cheerful colour.

Visitors to the NASA Plumbrook site in Ohio responded well to a bright colour scheme. Both these cases represented a biased sample of people who already had an interest in the subject.

Also, choice of colour will be conditioned by the type of landscape in which the machine is sited. For example, the MOD OA at Clayton, New Mexico, was in a fairground where a deliberately bold colour scheme worked well, but which could be quite out of place on a dour Scottish hillside.

Views On The Siting Of Machines: Size and Dominance

No clear message emerged from the literature on a preferred size of wind turbine, but Carlman considers that size and distance from the observer have to be treated together, in that these two factors combine to give an overall impression of dominance. Thayer and Carlman have expressed this in terms of the multiples of the height to the top of the rotor of the turbine from the observer. This is inadequate without also taking into account the effect of any hill on which the turbine may be built. Bergsjo, Nilsson and Skarbach (1982) identified four zones of visual intrusion thus:

1 Sweep Zone - radius of one blade,

2 Visual Intrusion Zone - in which a turbine is perceived as visually intrusive - 1 to 5 times the height of the top of the rotor, or down to an angle of inclination above the observer of 11 degrees.

3 Visual Dominance Zone - bounded by the maximum distance at which the turbine tower dominates the field of vision, 5 to 10 times the height of the top of the rotor, or an 11 degrees to 6 degrees angle of inclination.

4. Visibility Zone - Inside which a unit can be seen, but is perceived as belonging to the distant landscape.

The critical question seems to be:
At what distance from turbine(s) of different heights do people feel they can live comfortably without any sense of threat by, or fear of the wind turbine(s) and, if different, at what distance do people passing along a nearby road or railway accept machines as part of the landscape? Carlman investigated this for a 3MW, 70m diameter turbine on a 79m tower in broadly level country and found that:

- 50% of interviewees wanted a separation distance of 500m or more. That is five times the overall height, or less than an 11 degree angle of inclination.

- only 10% were prepared to accept a 300 - 400m separation.

Thayer found that there was a strong preference for wind turbines to be in the background, or far field, when presented with photographs of turbines at varying distances from the viewer. He showed turbines on a ridge at a distance of about 700m and then another photo showing machines at less than 100m from the camera. Wolsink supports Thayer's findings but neither offer sufficiently detailed guidance for siting purposes.

In Denmark the preferred separation zone for 60m diameter machines was over 400m. Since this would have precluded the siting of large scale wind turbines in Danish agricultural areas the Danish Ministry of Energy relaxed the separation zone to 200 - 300m.

The author's machine is clearly visible for about 5km along the Penryn to Helston road on which there average 6700 vehicle movements per day. The turbine is most prominent where the road passes within 2km of the site. When the machine was erected five people rang when they saw it for the first time. This included two news reporters. In all cases they had made more than three return journeys along the road before they had noticed it. In good visibility the machine is very difficult to see at over 7km from the site.

Windfarm Siting Criteria

Thayer reported preferences for:

a. Fewer, large (300 - 700kW) turbines rather than large (>100) numbers of smaller (<100kW) machines.

b. Orderliness, tidiness and professionalism in the appearance of the windfarm. There was a negative reaction to many closely spaced wind turbines and to more than two or three rows in any windfarm as this gave a messy and cluttered view. Typical spacings in the Altamont are seven diameters between rows and two diameters between machines in any one row.

c. All the wind turbines in any one group should be of the same design and should rotate at the same speed.

d. There should be open areas (variously defined) between different groups of wind turbines.

Availability Of Land For Wind Turbines

All commentators report a willingness of most landowners to sell, or lease, land for windfarm developments.

Views On The Operation Of Wind Turbines

Given the effort and money needed to build a wind turbine, and the apparently free income available immediately it is completed, the natural expectation of people who come to see it, or regularly pass its site, is that it should work. If these expectations are not fulfilled there is a very negative response. The author's turbine did not operate between September 1986 and the following February. (This was because the tripping time limits on the voltage and frequency of the incoming voltage so frequently went beyond the limits set by the Electricity Council that generation was impossible.) The farmer on whose land the machine was sited reported a stream of people coming to ask "Why isn't the windmill working?

Thayer cites the large number of inoperational wind turbines in the Altamont as the prime reason why people living close to the windfarms were much more negative in their attitude compared with those who lived further away and who were less familiar with them. Here, the belief that the machines were built as a tax shelter rather than a bona fide generating station fuelled antagonism towards the development.

Carlman reports that people living close to the two multimegawatt machines in Sweden were basically sympathetic towards operating problems experienced soon after their erection, but wanted to be given a complete account of these difficulties. They reacted against any statement which smacked of obfuscation, the public relations approach, or which talked down to, or was condescending towards, the inquirers. People associated with the wind industry, particularly actual or potential investors, say they have had a warmer regard for manufacturers who have been frank, and open about design or operating problems, than for those who have operated behind a cloak of secrecy or misinformation. The former were believed when they outlined their plans for dealing with the problems, the latter were not. (Private communication. Michigan Resources Corporation.)

All commentators stress the importance of informing and involving the local community in the decision making process relating to the siting of the wind turbine(s).

The Views Of Different Interest Groups

1. Believers and Non-Believers

People who had sufficient interest in the renewables to have developed a belief in their function, in terms of their non-pollution, their renewability and their relative safety, were prepared to overlook shortcomings in aesthetics and the fact that man-made structures now occupied previously virgin land. They were also more forgiving of operational shortcomings. People who did not have sufficient knowledge or interest to have become committed to the renewable energy ideal, merely reacted to the machines' appearance. In the cluttered, disordered and broken down outlook onto many of the Altamont windfarms, many became opponents of what they saw.

2. Politicians And The Media Do Not Represent The Majority View

Carlman found that two thirds of the local, regional and national politicians and administrators believed that the visual intrusion of wind turbines would not be accepted by the public, and used this as a reason for not pursuing wind energy. When the public were questioned, over 80% were not concerned about this issue. Similarly, Thayer reports that the Palm Springs action against the Bureau of Land Management and the windfarm operators of San Gorgonio was inspired by the city officials' expectations of a public backlash against rapid windfarm development. In fact, the public's reaction turned out to be complex and multifaceted.

In 1976 Ferber reported a more positive attitude towards wind energy by young people and the better educated. Ten years later Thayer reversed this finding by saying that this group criticised the Altamont development on grounds of tax avoidance and because it failed to live up to their expectations for order, tidiness, and competent operation. Thayer says that females and older people were more tolerant in this regard and sought fewer changes to the status quo.

Carlman explained that with a topic where there was a low level of technical understanding the beliefs and attitudes of many people were led by those in the "expert organisations", namely the utilities and the Departments of Energy. If these bodies had no genuine interest in the technology, or if their interest was perceived to be a public relations exercise as opposed to a serious attempt to use wind in their generating mix, then a negative attitude resulted, and vice versa.

Ignorance Of Wind Technology

All commentators reported a very low level of understanding about how a wind turbine actually works, how it delivers electricity to the system, and its role in an interconnected network. The most commonly asked questions at the author's turbine are:

1. What happens between the rotor and the generator?
2. How do the fantails work, how does the machine turn to face the wind?
3. What causes the machine to start, how does it connect with the grid, and how does it stop?
4. How does the generator actually feed electricity into the distribution network?
5. Where does this power go once it is in the network?
6. What contribution is this machine making to the local demand at the present time? The output is always fluctuating, surely this is a disadvantage?
7 How is it possible to sell electricity, surely that is illegal? I simply do not understand how electricity generated here can be used at your home, or at my home, as you say is permitted by the Energy Act.
8. What happens when the wind stops blowing, surely that is the main disadvantage with wind energy? Will any of the wind turbine's customers for electricity then be cut off?
9. What is the attitude of the SWEB - surely they disapprove of what you are doing?
10. Why aren't there more wind turbines, surely they cannot be economic?
11. Do you have to be here all the time to operate the wind turbine?
12. How tall is the tower, it looks shorter than I expected having seen it from a distance?
13 What happens in a storm?
14. Can you please describe the wind speed in miles per hour, or according to the Beaufort scale, because metres per second mean nothing to me.
15. I can understand variable pitch blades but I do not understand this idea of stall control.
16. For what percentage of the year does the machine operate? (There is much confusion between the output read off the kW meter at the site, the nameplate rating of the machine and the average output over the year.)

The concepts involved in the answers to questions 4, 5, 6, 7, 8, 15 and 16 are very difficult to explain satisfactorily in the short time available. The Use of System Tariff idea, SWEB (1987), is particularly difficult to get across since this is an hypothesised concept of a reality with which few are familiar. Neighbours of the machine who were told that most of their electricity now came from wind energy frankly disbelieved this to be possible and rang the local electrical shop where they were told that of course they were quite correct "the man is talking nonsense - all our electricity comes from up country".

10.4.2 Survey Of Attitudes Of People Living Near British Wind Turbines

In order to see how well the foreign experiences reported in the public opinion surveys transferred to people exposed to wind turbines in the UK, a questionnaire was devised and 62 interviews carried out with those people living closest to the wind turbines at Treculliacks, Ilfracombe, on Lundy and on Orkney. The results for Lundy were compromised by the influx of summer visitors at the time of the survey. There were significant regional differences. These are described in Martin Varley's BSc thesis, at the School of Environmental Sciences, University of East Anglia 1987. Where such differences have occurred, the Cornish response has been used.

This survey was carried out to help develop sensitive siting criteria. The number of respondents who live close to machines in the UK is really too low to provide a meaningful sample size and the replies should not be disaggregated. The following results should be seen as interim indications, not final conclusions.

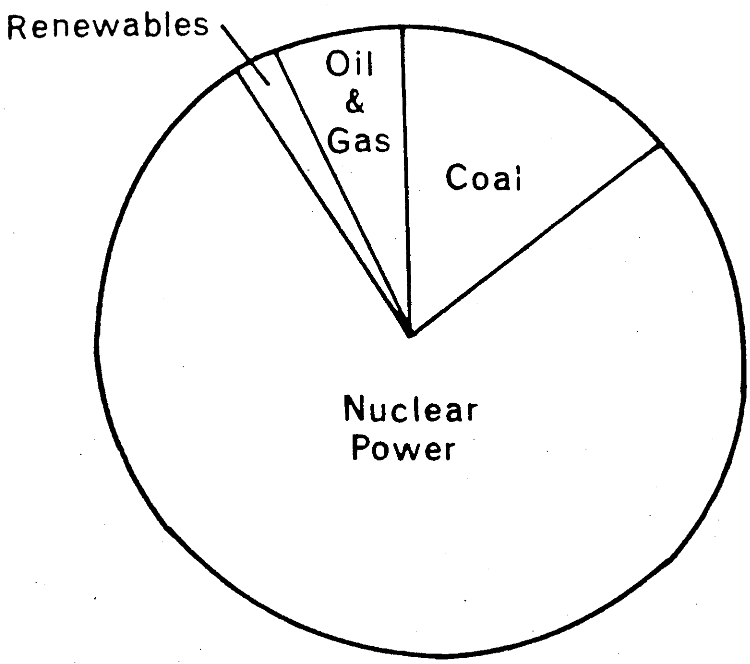
Question:
WOULD YOU LIKE TO SEE AN INCREASE, DECREASE OR NO CHANGE IN THE PROPORTION OF ENERGY SUPPLIED BY EACH OF THE FOLLOWING SOURCES:

- COAL
- NUCLEAR
- WIND/TIDE/GEOTHERMAL
- OIL & GAS?

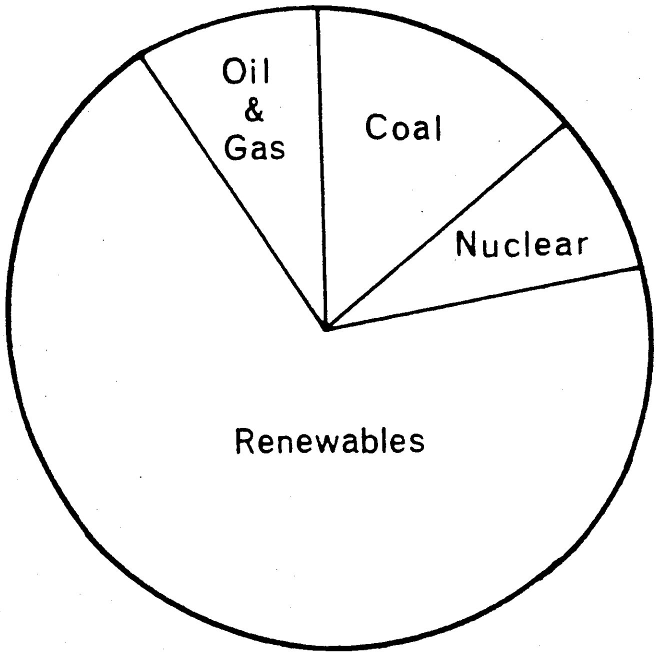
Over three quarters of the respondents wanted to see a decrease of supply from nuclear power. The majority of anti-nuclear respondents were women. Some people reserved judgement believing that they did not know enough about the issue and about 10%, predominantly males, wanted to see an increase in the nuclear industry.

Most respondents wanted the supply from coal to remain the same for fear that a decrease may cause unemployment.

Public Opinion On Preferential Change in Source Of Britain's Energy Supply.



Decrease



Increase

Figure 10a

Source: M.Varley 1987

There was an almost unanimous call for an increase in energy supply from the renewables on the grounds that the reserves of the fossil fuels were finite and that the nuclear industry had problems with waste. The respondents felt that effort should be put into developing renewables and wind and geothermal were mentioned most frequently. (Strictly speaking the latter is not truly renewable). See figure 10a.

Question:
DO YOU THINK YOUR TELEVISION RECEPTION IS AFFECTED BY THE WIND TURBINE?

Only one person said yes. This was for a portable set with a rudimentary aerial. Snow was seen on the screen. The set was 280m from the turbine when the latter was about 20 degrees to one side of the direct track from the receiver to the transmitter. The receiver was also well below the brow of a hill. A directional aerial was supplied to replace the original.

Question:
HAVE YOU EVER NOTICED THE LIGHTS FLICKERING?

No - in all cases. This is confirmation of the readings from a Dranetz transient recorder installed for a week at the closest property to the turbine at Trecullicks.

Question:
USING THE DISTANCE FROM YOUR HOUSE TO THE TURBINE AS A MEASURE OF MINIMUM DISTANCE FOR PEOPLE TO LIVE, WOULD YOU SAY THAT THE DISTANCE IS TOO SMALL, ABOUT RIGHT, OR TOO BIG?

If, for other reasons, people felt disadvantaged by the installation of the turbine then that was likely to affect their reply to this question. Whether or not the machine was visible from the house windows, either upstairs or downstairs, or from their garden also affected their response. An analysis of these interrelationships was made at all three sites. From this it emerged that people felt dominated by the machine when the angle subtended at the observer from the horizontal to the top of the rotor disc exceeded ten degrees. It should be emphasised that in most cases the turbines were not situated in the direction of the cherished aspect from the house and the angle of ten degrees applies to machines sited behind, or to the side of the main outlooks from the dwellings. This finding corroborates Carlman's results.

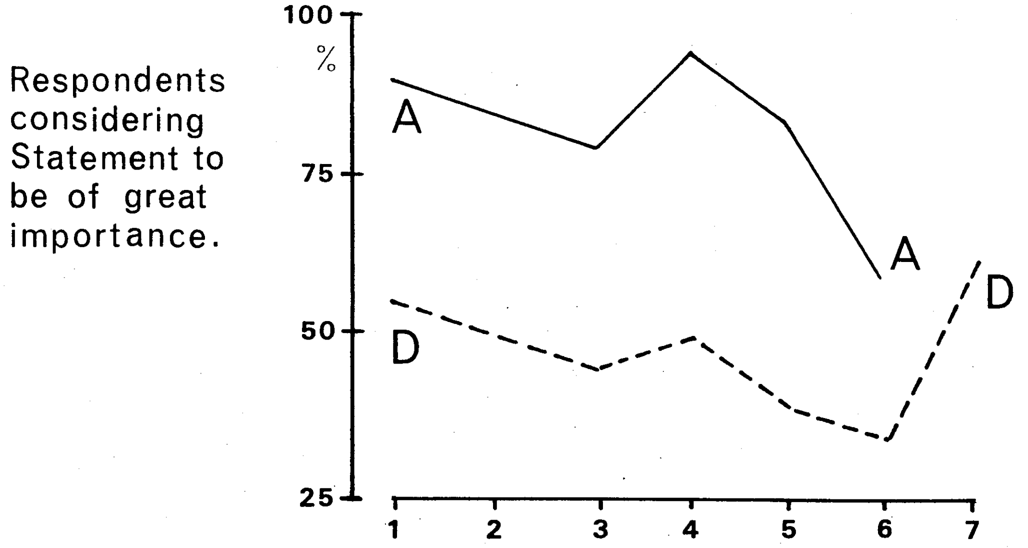
Question:
ASSIGN NUMBERS ON A SCALE OF 1 (SMALL) TO 3 (LARGE) TO CLASSIFY THE FOLLOWING ADVANTAGES AND DISADVANTAGES OF WIND ENERGY:

ADVANTAGES:
- CLEAN, DOES NOT POLLUTE THE ENVIRONMENT
- SAFE
- PROVIDES CHEAPER ELECTRICITY
- INFINITELY RENEWABLE
- WILL MAKE STOCKS OF COAL AND GAS LAST LONGER
- PROVIDES EMPLOYMENT

DISADVANTAGES:
- UNRELIABLE AS THE WIND DOES NOT ALWAYS BLOW
- EXPENSIVE TO RESEARCH AND BUILD
- SPOILS THE SCENERY, IS NOISY
- DISTURBS TELEVISION RECEPTION
- DISTURBS WILDLIFE
- LARGE NUMBERS ARE NEEDED TO PROVIDE THE SAME OUTPUT AS A COAL OR NUCLEAR POWER STATION.

The results are summarised in figure 10b. This confirms that people perceive wind to have more advantages than disadvantages. The fact that it is a clean source of energy, does not pollute the environment and will never run out were listed as the main advantages. Its role in employment generation, or in supplying cheap electricity was considered to be unimportant. For those people affected by noise from the wind turbines, this was seen as the main disadvantage and from all the respondents "noise was seen as the overriding environmental hindrance to the future of wind power" Varley (1987). Noise was considered to be more of a disadvantage than "spoiling the scenery". Again, those people who lived closest and felt dominated by the machine complained that it was spoiling the scenery, but otherwise this was not considered to be a major drawback. Some people said how much they liked to see the machine running, whereas nobody said they liked to hear it working.

The fact that large numbers were needed to provide the same output as a coal fired or nuclear power station was seen by many as the greatest operational disadvantage. Other anti-nuclear respondents replied that they would prefer to see a thousand wind turbines to living near a nuclear power station. The second biggest disadvantage was the unreliability of the wind, as it does not always blow.



Total Sample. Attitudes Towards Wind Power: Advantages: A, & Disadvantages: D.

Values correspond to the following advantages:

A
1 - Clean, does not pollute the environment
2 - Safe
3 - Provides cheaper electricity
4 - Infinitely renewable
5 - Will make stocks of coal and gas last longer
6 - Provides employment

Values correspond to the following disadvantages:

D
1 - Unreliable as wind does not always blow
2 - Expensive to research and build
3 - Spoils the scenery
4 - Noisy
5 - Disturbs television reception
6 - Disturbs wildlife
7 - Large numbers of turbines are needed to provide the same output as a coal or nuclear power station

Source: M Varley 1987

Figure 10 b

Question:
AS WIND POWER DEVELOPS, MORE SITES FOR TURBINES WILL BE NEEDED. TELL ME WHETHER YOU WOULD FIND THE FOLLOWING SITES ACCEPTABLE OR UNACCEPTABLE?

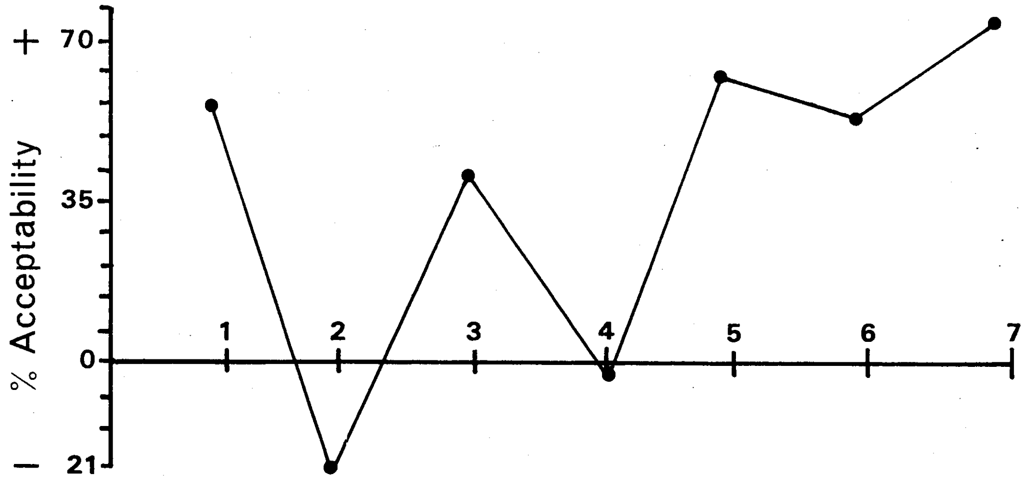
- NEAR THE COAST
- IN A LINE ALONG A ROAD
- IN A LINE ALONG A RIDGE OF HILLS
- IN AN AREA OF SCENIC BEAUTY
- IN A LARGELY MAN-MADE LANDSCAPE
- IN A CLUSTER
- AS AN ISOLATED TURBINE
- OFFSHORE.

The results are shown diagrammatically in figure 10c. This reinforces the impression that there is no strong objection to wind turbines in any landscape type other than in an Area of Outstanding Natural Beauty. People are prepared to accept turbines near the coast, on hills and in lines along ridges, but objected to them along roads because they might distract the drivers and because they would mimic telegraph poles.

Question:
WOULD YOU PREFER TO SEE A GROUP OF WIND TURBINES OR ONE ON ITS OWN? WOULD YOU RATHER SEE FEW LARGER ONES OR MORE SMALLER ONES OR NONE AT ALL?

The 10% pro-nuclear faction wanted to see no machines at all. For the rest, there was no particular preference. See figure 10d. In another unpublished survey of public attitudes to wind energy, Professor Lee (private communication, 1987) showed to his respondents photographs of wind turbines. His interviewees had no direct, personal experience of wind machines. The photographs represented a series with each print showing an increasing number of turbines. He found steeply rising resistance once machine numbers exceeded about six per group. This did not emerge in our survey which only included people with direct experience of turbines, but we did not use photographs in association with the question.

Attitudes Towards Siting Turbines In Different Landscapes.



1 Near to the coast.
2 In a line along a road.
3 In a line along a ridge of hills.
4 In an area of scenic beauty.
5 In a largely man-made landscape.
6 In a cluster.
7 Offshore.

Source: M. Varley 1987

Figure 10 c

Question:

DO YOU PREFER TO SEE THE TURBINE STATIONARY, RUNNING SLOWLY, RUNNING AT FULL SPEED, OR DO YOU HAVE NO PREFERENCE?

FULL SPEED	-	10 respondents
NO PREFERENCE	-	11 respondents

Question:

MOST OF THE ELECTRICITY YOU GET COMES FROM THE WIND TURBINE. WOULD YOU BE INTERESTED IN OWNING PART OF THE TURBINE IN ORDER TO REDUCE OR ELIMINATE YOUR ELECTRICITY BILLS?

The answers at Treculliacks were:

YES	13 respondents
NO	2 respondents
MAYBE	6 respondents

Question:

WOULD YOU LIKE MORE INFORMATION ABOUT THE TURBINE AND ITS OPERATION?

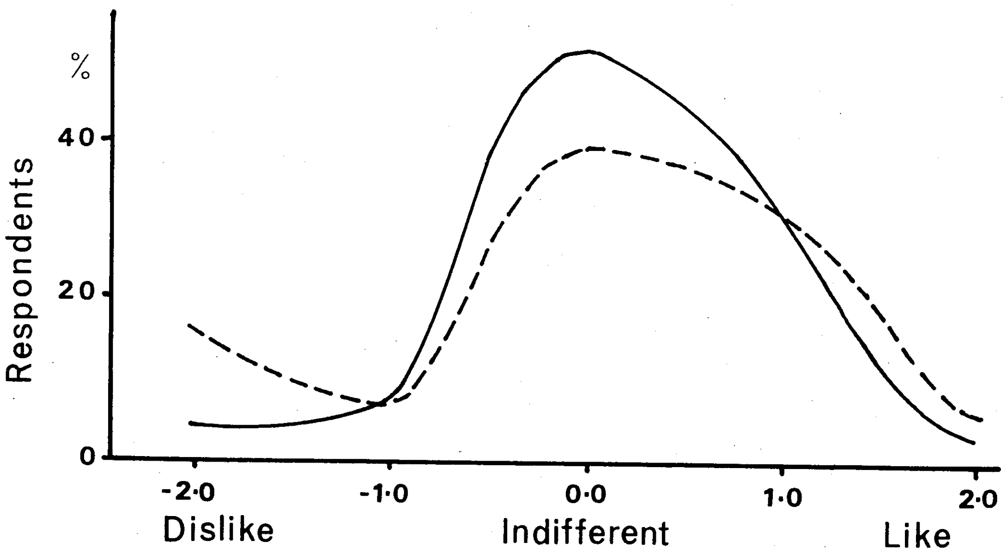
YES	10 respondents
NO	12 respondents

Notwithstanding the composition of these replies the interviewer reported that most respondents complained about the lack of public consultation prior to the erection of the machine. Although notice of the planning application was posted on telegraph poles and in the local press, the people living nearby had no clear idea of what was involved. They felt let down because a fuller account had not been given to them prior to the planning decision.

Although the results for Lundy were not tabulated the interviewer reported that there was universal support for the machine since it had made such a difference to their lives in terms of having electricity for longer periods and being able to heat and rent the properties on the island for a longer proportion of the year. Here the link between the turbine and local advantage was clear.

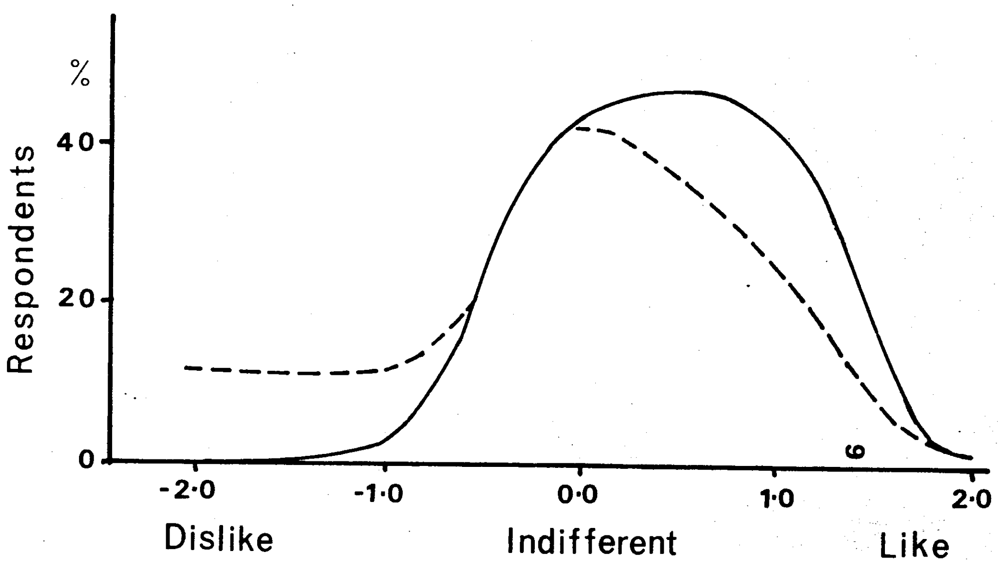
The surprisingly high percentage (59% - yes, 27% - maybe) of people at Treculliacks who said they would be interested in investing in the turbine to offset their electricity bills gives a clear indication of how people living close to turbines could be involved directly and beneficially in their installation and operation. This might avoid some of the usual resistance to outside agencies imposing themselves and their impedimenta onto host communities, who then have to suffer the intrusion, but get none of the benefits. The notion of a jointly

Local Attitude Towards Respective Wind Turbine With Respect To Stated Variables.



(a) By Sex. Solid Line: Females, Broken: Males.

Figure 10 d



(b) Affected (Broken Line) Or Unaffected (Solid).

Source: M. Varley 1987

Figure 10e

owned machine is virtually impossible at present due to institutional impediments. However, if the proposals in Cmnd 322 "Privatising Electricity" are put into effect, exciting possibilities could arise for locally financed and run energy groups clustered around their own sources of renewable energy supply. This has come about in Denmark.

If seeded with care and perception, and in a way which financially benefits people living close to potential wind turbine sites then wind energy implementation could possibly be led and initiated by local interest groups rather than opposed by them. The fact that it is possible to insure this type of plant against loss of income from a breakdown will be important in encouraging people to invest. So too will the notion of diesel back-up.

Question:
DO YOU LIKE OR DISLIKE THE TURBINE? IF YOU DISLIKE IT, WOULD YOU LIKE TO SEE ITS:

- COLOUR CHANGED
- SHAPE CHANGED
- SIZE CHANGED
- REMOVED ALTOGETHER
- OTHER?

The results are shown in figure 10e. In interpreting these graphs it is necessary to emphasise how the three sites differed in terms of the distances at which people lived from the machines:

Treculliacks The average distance of the respondents' properties was 640m with 13 habitations at less than 600m from the machine. The range of separation distances was from 280m to 1130m. Of the three sites considered, this machine was located closest to most dwellings.

Ilfracombe The average distance was 830m, only 5 respondents lived less than 600m away and even then some of the closest properties were hidden from the site by high ground. The range of separation distances for respondents' houses was from 380m to 2400m.

Orkney The average distance was 1750m, no one lived closer than 1km to the WEG machine and the furthest respondent lived at 2600m. There are no potential sites in Cornwall where the nearest property is over 800m from any potential wind turbine.

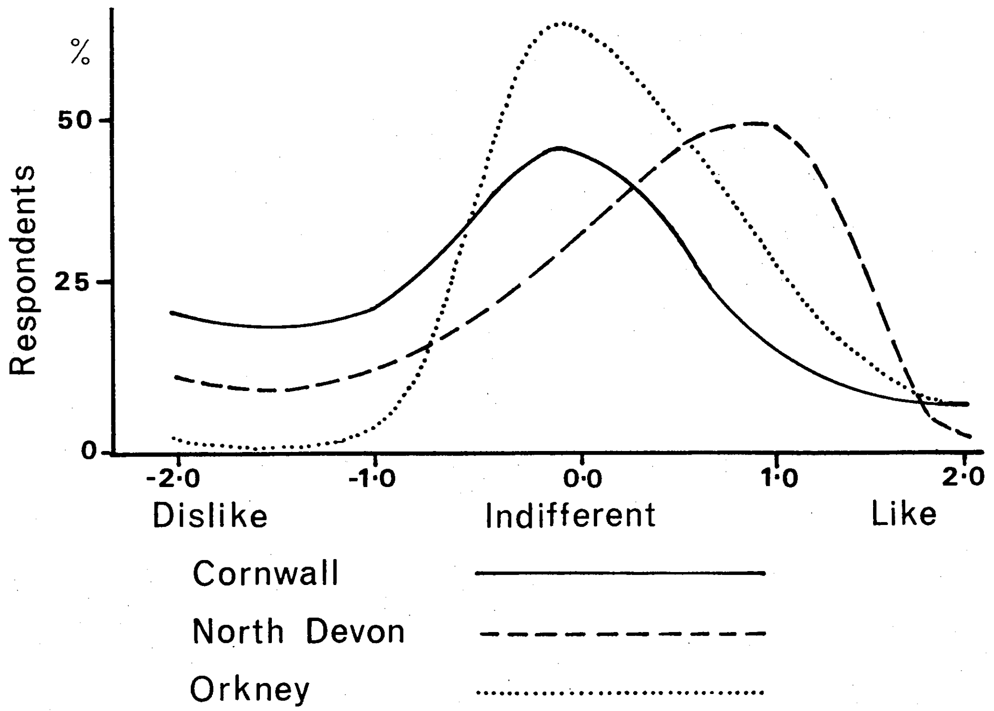
Indeed in the whole of England and Wales in areas outside the AONB's there are only 457 sites with 800m separation distances and of these 297 have severe access and other problems leaving only about 160 viable sites of this size. Williams (1987). Therefore, the Orkney response should be interpreted with caution in respect of its application to Cornwall, or to the rest of England and Wales.

The total sample shown in figure 10g reveals that about a fifth dislike the machine with the balance not caring either way, or liking it. Figure 10d shows that in the group who disliked the machine, there were more men than women.

Figure 10e is most instructive. This shows that dislike of the machine was largely coincident with the group of people who felt affected by it - primarily by noise and domination. Some believed their properties to have been devalued.

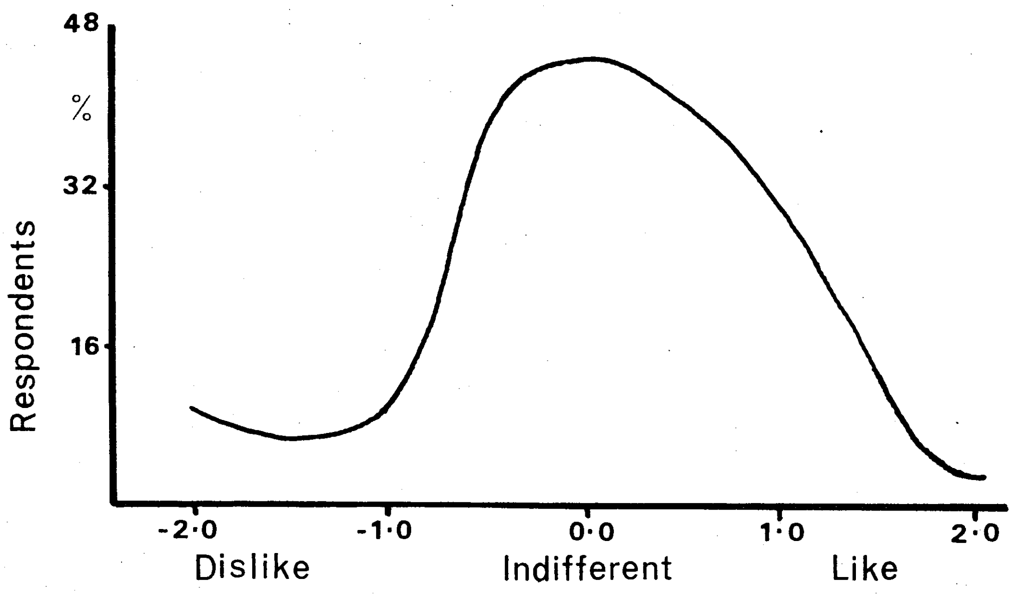
Figure 10f confirms this effect with maximum dislike registered at the site where properties were closest, and minimum dislike where it was farthest away. There were also other factors on Orkney such as employment opportunities and attitudes specific to an island community which probably affected this result.

Regional Attitudes Towards Respective Wind Turbines.



Source: M.Varley 1987

Figure 10 f



Total Sample Attitude Towards
Respective Wind Turbines.

Source: M.Varley 1987

Figure 10g

10.5 The Public's Perception of Wind Turbines: Conclusions

For people who have not been affected by wind turbines there is a very high level of popular support. There is a poor understanding about the way in which turbines work and some negative attitudes to wind are based on misconceptions. These could possibly be put right by better information on the subject.

On the other hand, people who feel they have been adversely affected in their homes by the erection of a wind turbine - primarily in respect of noise pollution and, in a few cases, compounded by feelings of being dominated by the machine, have reacted with considerable hostility towards it. This has resulted in regional television and press coverage, the lobbying of local council officials and the granting of temporary, not permanent, planning permissions.

By using machines designed primarily for the quietness of their operation, by specifying machines of a size and capacity which will not cause widespread noise pollution, and by being sensitive in choosing positions for these turbines in respect of the favoured aspects from the nearest habitations it should be possible to tap a large resource without adversely affecting the people who live closest to the sites.

10.6 The Public's Perception Of Wind Turbines: Recommendations

There is the possibility of capitalising upon the very popular notion of getting energy from a free fuel by offering:

1 Investment opportunities to the neighbouring residents who have said they are interested in reducing their electricity bills, in this way.

2 Income and casual labour opportunities where the machine(s) are installed.

3 Fair ground rents for the turbines and their access routes, and for any land which needs wind rights protection.

4 Reasonably generous compensation for land and crops damaged during the installation.

5 Earning opportunities for people living at any property which is unavoidably overlooked (not dominated) by the development. This apparent disadvantage may be turned to good effect by offering payment for their informal security surveillance of the installation.

The Public's Perception of Wind Turbines References

ARKESTEIJN, L. A. G. (1984)
"Physical planning and wind energy in the Netherlands." European Wind Energy Conference, Hamburg.

BERGSJO, A., NILSSON, K.
"Wind power in the landscape." Fourth International Symposium.

CARLMAN, INGA. (1984, 1982)
"The views of politicians and decision makers on Planning for the use of wind power in Sweden." Procs European Wind Energy Conference, Hamburg, pp 339-343. 1984.

"Wind energy potential in Sweden: The importance of non-technical factors." Fourth International Symposium on Wind Energy Systems Sept 21-24, Vol 2, pp 335-348. 1982.

"Public opinion on the use of wind power in Sweden." Institute for the Management of Natural Resources, Stockholm University. 1982.

DANISH MINISTRY OF PLANNING (1981-1982)
Store Vindmoller i Denmark. Vols 1-4.

ENGSTROM, S., PERSHAGEN, B. (1980)
"Aesthetic factors and visual effects of large scale wind energy conversion." Final Report NE 20 of task A-S.I.E.A. National Swedish Board for Energy Source Development.

FERBER, R. (1977)
"A pilot study on public reactions to wind energy devices" pub. Mitre/ERDA/AIAA 2nd Workshop on Wind Energy Conversion Systems, Washington. DC.

FREEMAN, C.M. (1976)
"Energy landscape." Center for Design Research, Department of Environmental Design, Univ. of California. Davis, California 95616.

FREESE, STANLEY (1971)
"Windmills and millwrighting". David & Charles.

GOODEY, B.
"Perception of the environment." Centre for Urban studies. University of Birmingham.

HOINVILLE, G., & JOWELL, R.
"Survey research practice." Heineman pp 27-53.

LITTLE, R.J de (1972)
"The windmill, yesterday and today" John Blake.

MACKIE, C. (1987)
"Wind energy implications for rural communities." Procs: BWEA Conference, Edinburgh, April.

MILLER, J. (1987)
"Environmental assessment of aerogenerator project, Susetter hill, Shetland." Procs: BWEA Conference, Edinburgh, April.

RASMUSSEN, S. (1986)
"Siting of wind turbines." Wind Energy Research and Development, Danish Ministry of Energy.

ROGERS S.E., (1975, 1977, 1976)
"Environmental effects of wind energy conversion systems." Published by. Mitre/ERDA/AIAA 2nd Workshop on W.E.C. Washington DC.

"Wind energy conversion - environmental effects assessment." published by US Dep. Energy, 3rd Wind Energy Workshop.

"Evaluation of the potential environmental effects of wind energy system development." Battelle Columbus Labs. Aug. 193pp ERDA/NSF/07378.75/1.

ROGERS, S.E., CORNABY, P.R., STICKSEL, P.R., & TOLLE, D.A.
"Environmental studies related to the operation of wind energy conversion systems." Battelle Columbus Labs, Final Report, C000/0092-77/2.

SKARBACH, E. (1982)
Wind energy systems, Stockholm Sept 21-24.

SOUTH WEST ELECTRICITY BOARD (1987)
Use of system tariff.

THAYER, R.L. (1986)
"Altamont: public perceptions of a wind energy landscape." Center for Design Research, Davis. C.A.

U.K. DEPT. OF ENERGY (1979)
"Environmental impact of renewable energy sources." Published by ETSU/AERA Harwell, March 20pp.

VARLEY, M. (1987)
BSc Thesis, Department of Environmental Science, University of East Anglia.

WAILES, R. (1948)
"Windmills in England." The Architectural Press. London.

WILLIAMS, G.J. (1987)
Unpublished survey.

WOLSINK, M. (1986)
"Public acceptance of large WECS in the Netherlands." <u>Procs European Wind Energy Conference</u>, Rome, Oct pp 587-592.

YOUNG, P.V. (1983)
"Scientific social surveys and research." Prentice Hall, 4th Edition pp 193-205.

11. WIND TURBINE CAPITAL COSTS

Abstract

In order to provide information on the viability of the various sites in Cornwall, commercial quotations were received from most European manufacturers of ex-factory wind turbines. In addition, the make-up of machine costs was checked by getting quotations for machine components. These methods gave a high degree of reliability up to about 40m diameter, beyond which the data was less reliable and modelling techniques had to be used.

Grid connection costs were assessed for every one of the 1511 prospective turbine sites and average values derived from this total were used in the study.

Commercial costs for state-of-the-art machines were then incremented in three ways:

1 To allow for the higher installed capacity needed to optimise output from the range of wind speeds at the best Cornish sites. This raised installed capacity from 420 to 520 watts per swept square metre with a short term overload capability of 600 watts per swept square metre.

2 20% was added to blade costs to allow for the expense of improving blade reliability.

3 5% was added to current commercial prices to allow for noise attenuation measures.

This resulted in average installed costs for single quiet machines in the 15m to 25m diameter range of £295 per swept square metre (Oct 1987) and £280 per swept square metre when site rated capacity was fixed at 2.5MW. Beyond 25m diameter, costs rose to just above £300 per swept square metre.

When these results were further corrected for array losses and for the increase of wind speed with height, it was found that there was little change in the achievable cost of energy delivered over the range of machine sizes from 15m to 70m. Here it was assumed that the modelled predictions of capital costs for large machine of 40m to 70m diameter could be realised in commercial practice, but the odds are against this coming about in the near future.

Between 15m and 40m diameter there is no strong case on cost grounds for using one size of machine in preference to another. The choice of optimum machine size is more likely to be determined by other factors such as commercial risk, the gross resource which can be captured and environmental factors.

11.1 Wind Turbine Capital Costs: The Aim

We need to know wind turbine capital costs in order to match these with cash income from the machine so that we can then judge which of the prospective wind turbine sites can deliver energy at a rate of return on capital which is acceptable to the electricity supply industry.

11.2 Wind Turbine Capital Costs: The Method

The literature was searched for descriptions of the relationship between turbine costs per swept square metre and diameter.

Those European manufacturers of machines who had already sold wind turbines to utilities were asked to quote the ex-factory prices for their products as of October 1987. This gave a state-of-the-art trend line on figure 11b which ranges from 15m diameter and 50kW capacity to about 40m diameter and 750kW capacity. The trend line is derived from the lowest priced, commercially available machines and ignores those costing more than £250 per swept square metre ex-works. This is intended to mimic the approach of most buyers in the only competitive markets for wind turbines, namely Denmark and California.

The site survey will show (chapter 15) that rural settlement patterns dictate that there are less than a half dozen parcels of land in all of England and Wales which could support substantial windfarms on the scale of those in the United States. The great majority of sites limit the size of any windfarm to less than about 2.5MW. For reasons of cost and local availability, this means that wind energy installations will normally feed into the Area Board's 11kV network and not into the 132kV, or higher voltage systems. The capacity of most existing 11kV lines in Cornwall is 3MW. By allowing for a 20% overload, 2.5MW was then taken as the unit rated size for the purchase of wind generating capacity by an Area Board. Grid connection costs and the number of turbines purchased were geared to this capacity. For comparison, costs were also derived for the largest single machine that a site could accommodate.

The grid connection costs were assessed for every site by measuring the distance from the turbine(s) to the nearest part of the 11kV network and entering current prices for transformers, HV switches, isolators, earthing, substation civil works, cable, jointing, wayleaves, trench digging, lightning arresters, connection to the overhead system and the upgrading of that system to the nearest three phase supply.

To check the reasonableness of the commercial quotations and to provide individual trend lines of component costs as a function of size, the cost analysis of all the components of the author's machine was used as the reference point near the lower end of the cost/diameter scale. Specifications were laid down for similar machines of 20.9m, 30.27m and 35m diameter and commercial quotations were received for components for these sizes.

Some component costs were available for machines of between 40m and 70m diameter. Where these were not available, the trend line up to 40m was continued to 70m by using the theoretical treatments which forecast the change of component weight with increasing diameter.

11.3 Wind Turbine Capital Costs: Work Done

11.3.1 Literature Review Of Costs Per Swept Square Metre As A Function Of Wind Turbine Diameter

The overall shape and direction of the national wind energy programmes in the majority of developed countries was laid down in the late nineteen seventies. The Departments of Energy and the utilities believed that in order to exploit wind energy on a scale which was significant in the national context it would be necessary to build individual machines with multi-MW ratings. At that time, the idea of an equivalent capacity in medium size machines was not contemplated and the word "windfarm" was not in common usage.

It was thought that large machines would bring economies of scale and that their tall towers would further reduce the cost of energy by exposing the rotors to much higher wind speeds. Honneff, Kleinhenz and Hutter in Germany and Palmer Putnam in the USA before and during the last war produced cost/diameter studies which claimed that machines from 45m to over 130m diameter were the optimum size. This view was widely adopted for most of the nineteen seventies.

Professor Elliott at Birmingham University appears to have been the first person to question the "biggest is best" philosophy in Applied Energy in 1975. He divided the elements of a wind turbine into those where specific cost varied little with diameter such as the electrical system, and those where the material used increased as the cube of the diameter when energy capture only increased as the square of the diameter. This formula he applied to the blades and the tower and as a result he proposed machines of about 15m diameter as the optimum. This was prophetic since from 1983 to 1987 the Vestas 55kW machine at 15m diameter happened to provide the lowest cost per swept square metre ex-factory.

All of the authors cited in the references broadly agree that the graph of cost per swept square metre as a function of diameter is roughly U shaped. See figure 11a. This is because very small machines of up to about 5m in diameter suffer from:

- a disproportionately long tower compared with the rotor diameter.
- high specific costs when these are corrected for efficiency in gearbox and generator components.
- poor aerodynamic efficiency due to low Reynolds number.

At the other end of the scale, very large machines eventually suffer from the square cube law as described by Elliott and because:

Cost (f) Diameter Predictions 1980.

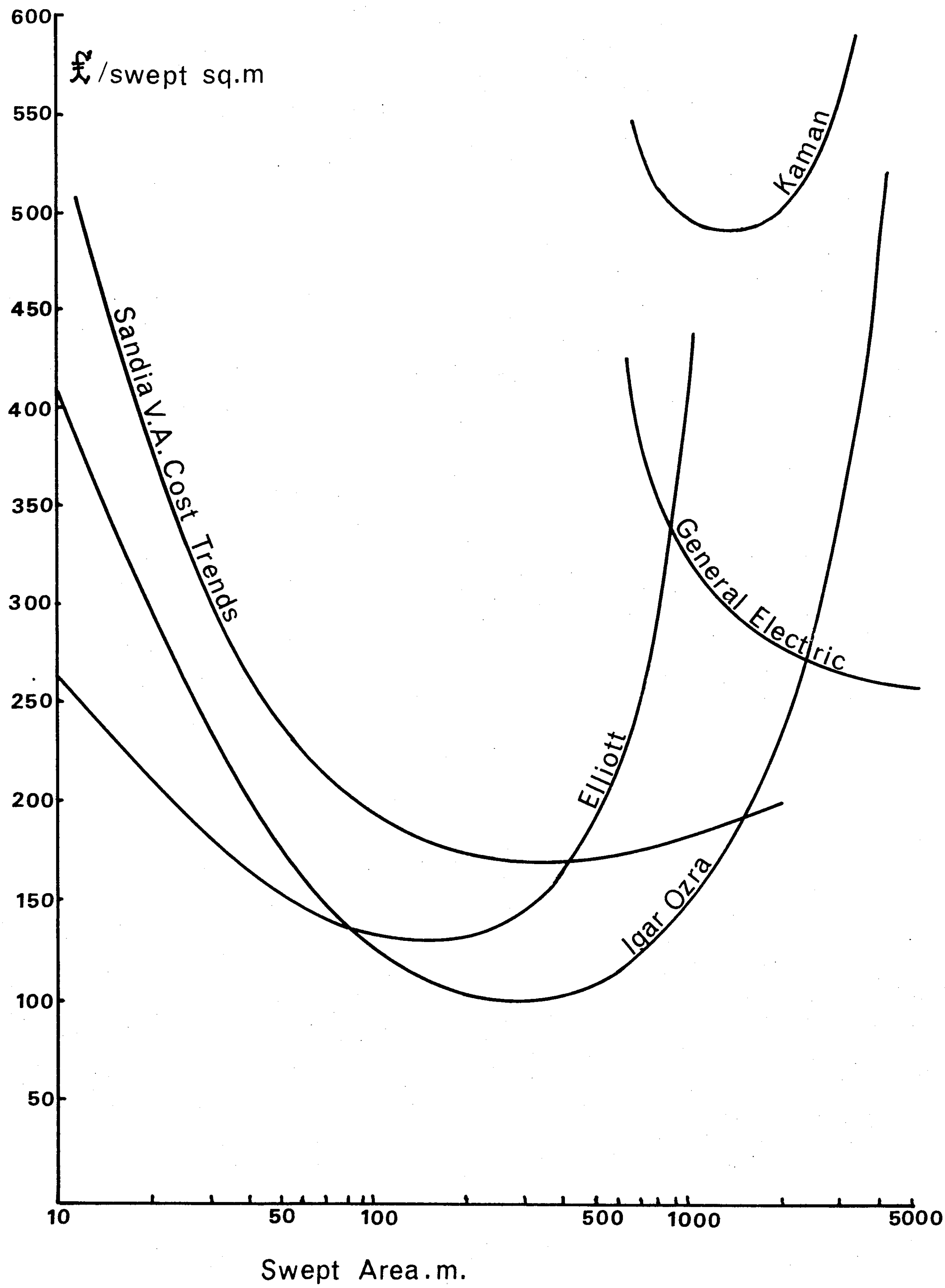


Figure 11a

- installation costs for cranage and its insurance costs become particularly onerous beyond about 45m diameter.
- small and medium size machines can select over two thirds of their components from long run, standard, industrial items. In large machines this accounts for less than a third of their costs.
- torque varies as diameter cubed.
- tooling costs are spread over fewer machines per unit installed capacity and commercial and technical risks are higher, thus encouraging firms to add substantially to cost prices.
- fewer firms will have the technical resources to design, analyse and construct such machines so there will be less competition and prices will rise.

Therefore, although many claimed that the specific capital cost trend will ultimately be towards higher costs as diameter increases, there is no consensus as to the point at which the right hand arm of the U curve will start to lift from its flat bottomed trough.

The Danish manufacturers and Follings say that 35m is the threshold, whereas Hau claims 50-60m. However Hau's claim is based on the idea of a wind shear exponent of .142 whereas the field work on typical Cornish hill top sites shows that for wind turbines there is very little relative gain in energy until well above 60m in hub height. This is because the terrain has tended to make vertical the shear profile from about 12.5m above ground level to beyond about 60m after which the increase in wind speed is only gradual.

Several commentators have assumed that cost savings could be made by specifying higher tip speeds and lower solidity, but this is not practical for the great majority of sites because it will exacerbate the already serious noise problem from large machines. The same difficulty applies in reducing the number of blades to one. Most commentators have not explored the effect of grid connection and erection costs on the total capital cost but have relied on ex-factory prices. Others are modelling the effect of size on a few components which make up about a third of the total installed cost of a wind turbine.

To complement that method, the next section is based entirely on the cost of commercial machines, a breakdown of their component costs, commercial prices for erection in Cornwall and grid connection costs for the average distances involved per turbine size for all 1511 Cornish sites.

11.3.2 Current Commercial Wind Turbine Costs Oct 1987

To determine the costs of wind turbines, European producers of medium to large machines were asked to quote their ex-factory prices in October 1987. Figure 11b summarises their replies. Cost per unit swept square metre is used as a yardstick since rotor swept area is the primary determinant of energy capture. The most economic machines had an installed capacity averaging 420W per sq m.

The Danish manufacturers (figures 3,4,5,6,7,9,10 on the graph) include delivery prices to England. These are some 40% below most prices quoted from other countries. This is largely because Denmark is the only European country with an active home market with over 2000 turbines installed, and a current annual production including exports expected to be up to 500 machines in 1988. About half will be sold to Danish utilities. The average machine capacity of all sales is expected to be 140kW. Danish manufacturers are confident of keeping specific unit prices level up to about 40m diameter and 750kW installed capacity, but they expect unit prices to rise beyond that point. This view is endorsed by the trendline on the graph in figure 11b which has been transferred to figure 11g for use as the reliable datum for the sum of the component costs.

Blade specific weights and costs as a function of diameter are shown on figure 11c. The heaviest blades also show the steepest rise in specific weight with increasing diameter. Only the lightest blades follow Ljungstrom's theoretical predictions (1977). Gear costs in figure 11d show a change in the slope of the graph at the point where double reduction gives way to triple reduction.

Tower costs in figure 11e show two distinct trends not obviously related to allowances for different loadings from fixed or variable pitch blades, or between stiff and soft towers. (Hardly anyone designs stiff towers anymore). One specific weight trend shows increasing weights with increasing diameter, the other shows a very flat characteristic. Van der Borg and Stam (1986) claim that towers built in Denmark, Holland and Germany in accordance with the estimated loads given either explicitly or implicitly by each of those country's design codes have led to conservative tower design. It is noted that only one of those country's machines figure in the lower curve and that is in a country where the code is advisory, not mandatory. The lower curve is populated by machines from countries not in the above group and represent figures for second or third generation machines from companies with a strong structural

Ex-Factory
Wind Turbine Costs
(f) Diameter.
(October 1987)

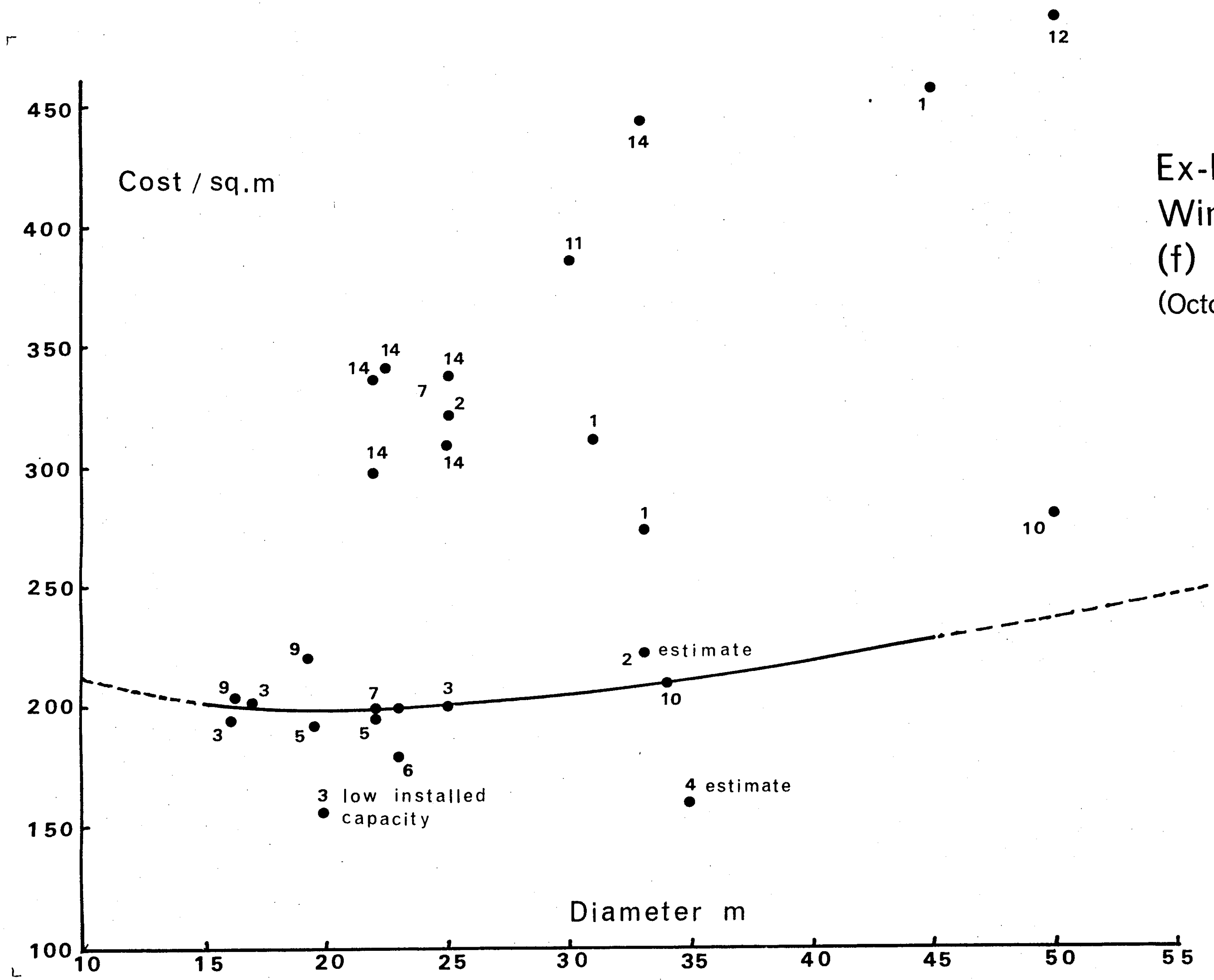


Figure 11b

Blade Costs (f) Diameter.
per Swept Sq.m (October 1987)

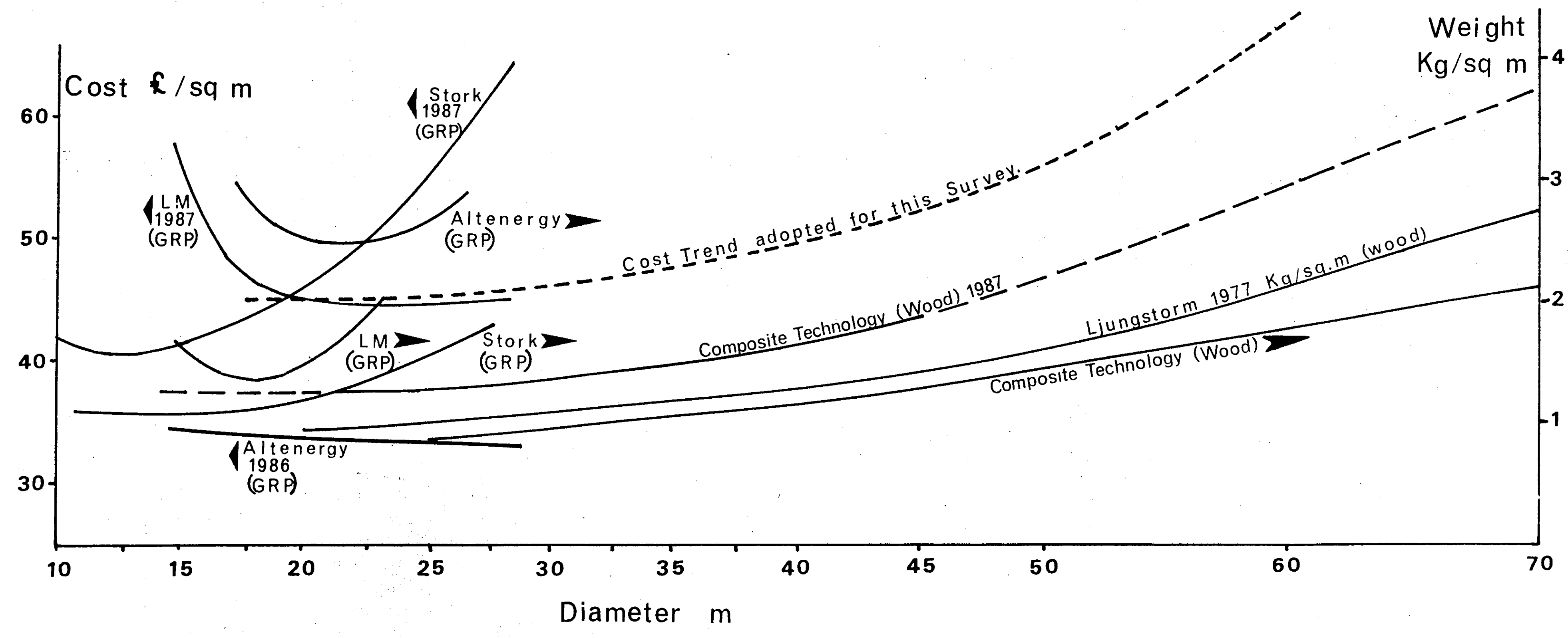


Figure 11c

Gearbox Costs (f) Diameter
($\lambda = 6$) (October 1987)

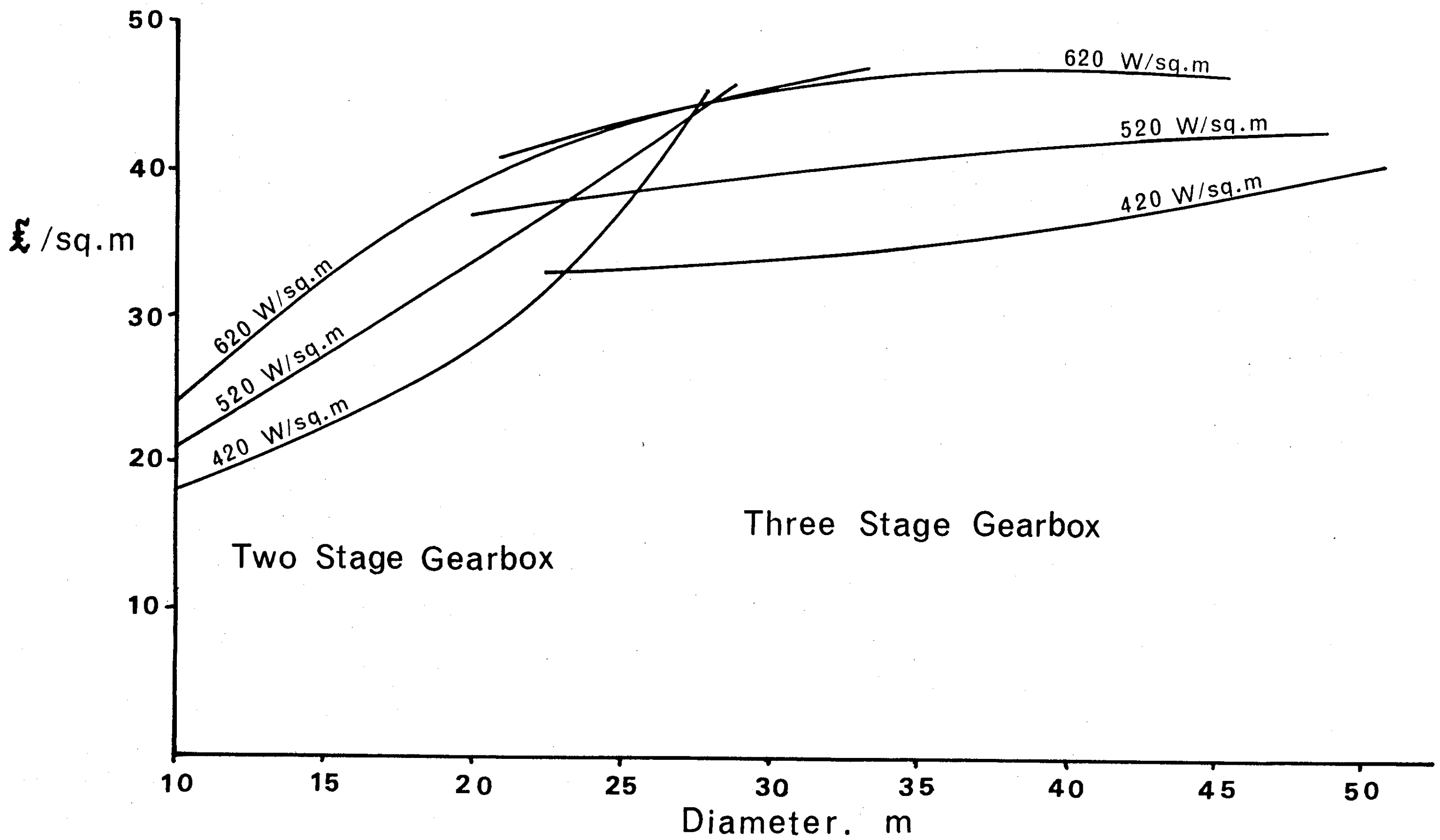


Figure 11d

Tower Weights (f) Swept Area.
Cylindrical Steel Towers.

		Type.	Pitch.	Betz Code.
1	HMZ	C	V	Yes
2	MOD 2	B	F	No
3	MOD V6	B	F	No
4	W.T.S.	C	V	No
5	Newecs 45	A	V	Yes
6	Windane 40	A	V	Yes
7	Newecs 22	D	V	Yes
8	Windane 31	D	V	Yes
9	Windane 34	A	V	Yes
10	Howden	B	F	No
11	Howden	B	F	No
12	WEG	C	V	No
13	Windworld	D	F	Yes
14	W.P.I.	C	F	Yes
15	MOD 5A(1)	not built		No
16	MOD 5A(2)			No

All Upwind
except No.4

Key:-
A Cylindrical.
B " " on Frustrum.
C Tapered, Poly: X-section.
D Step Tapered.

F Fixed.
V Variable.

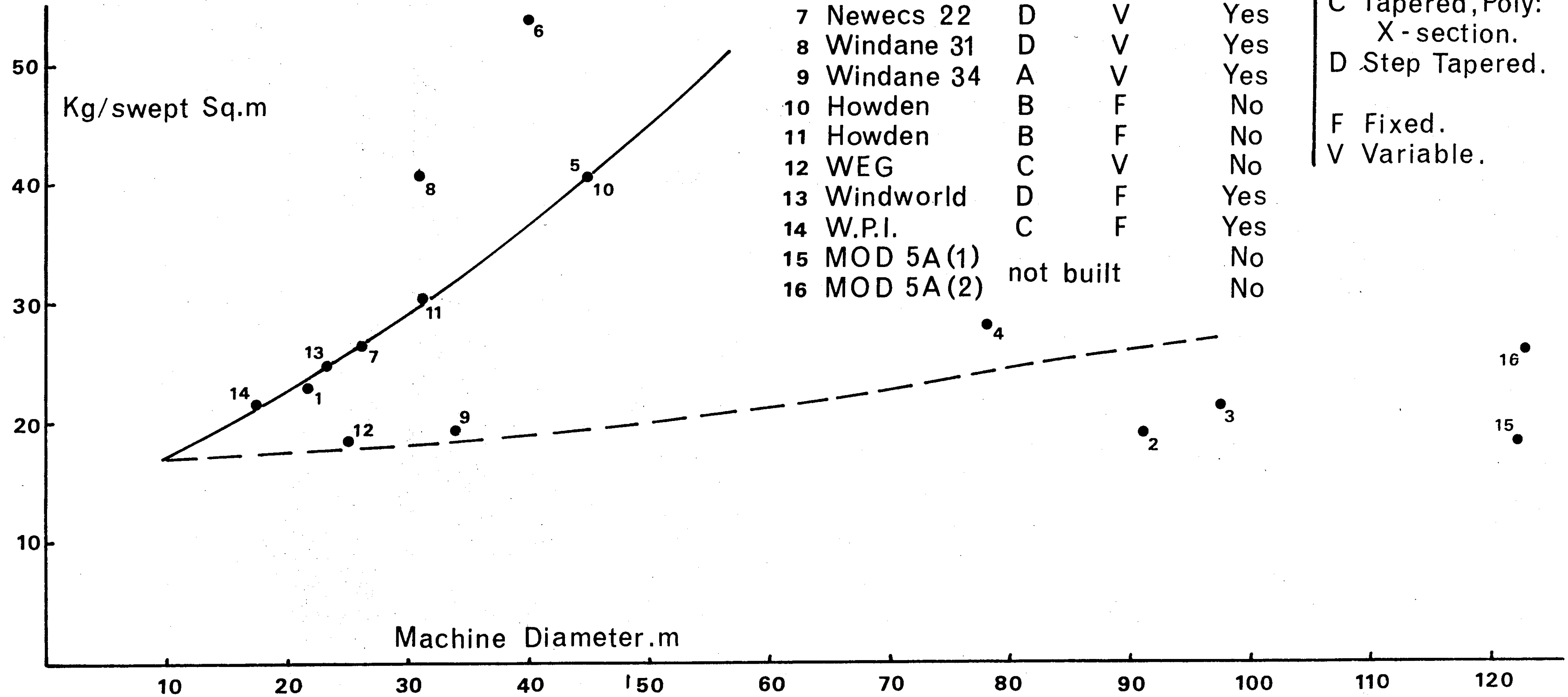
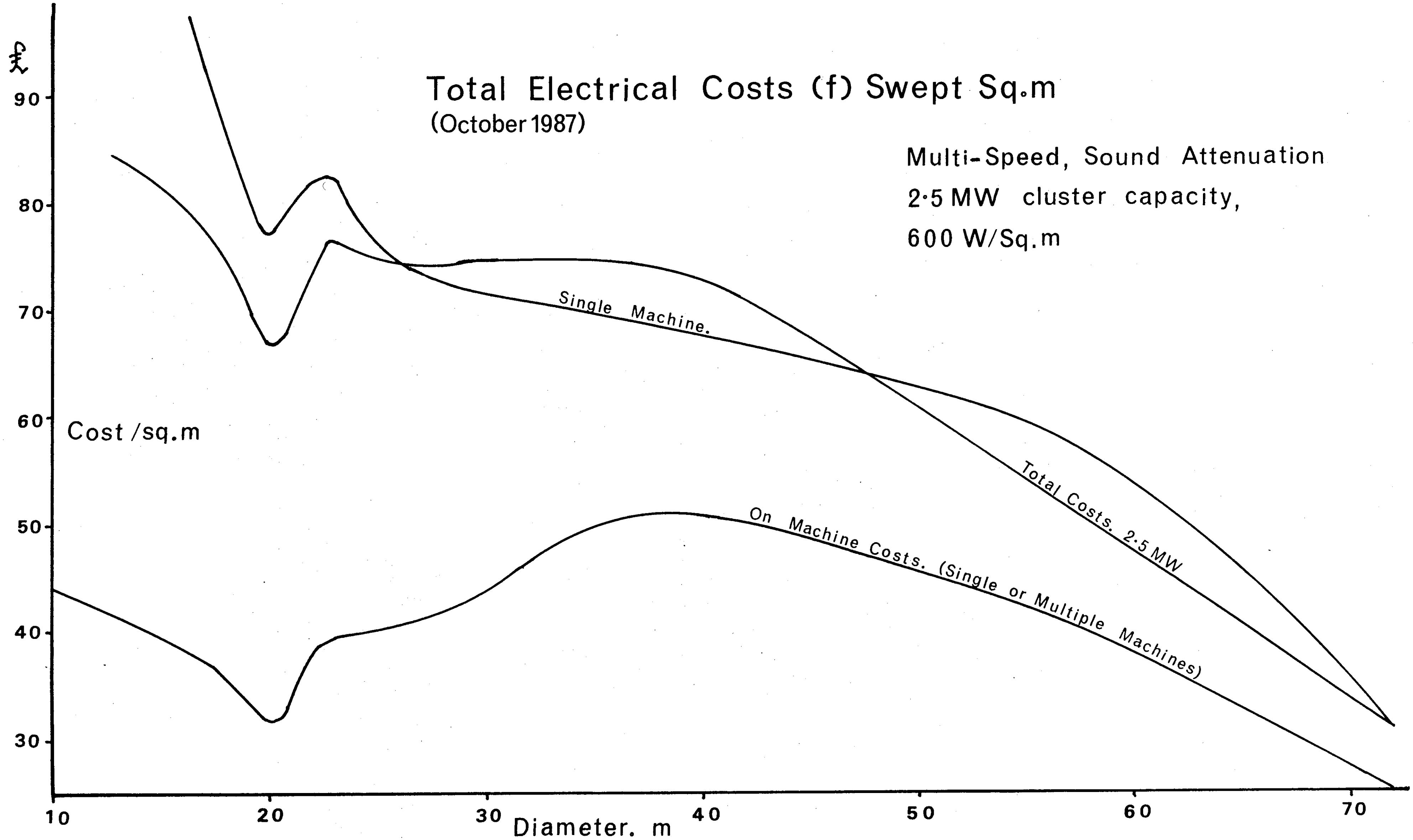


Figure 11e

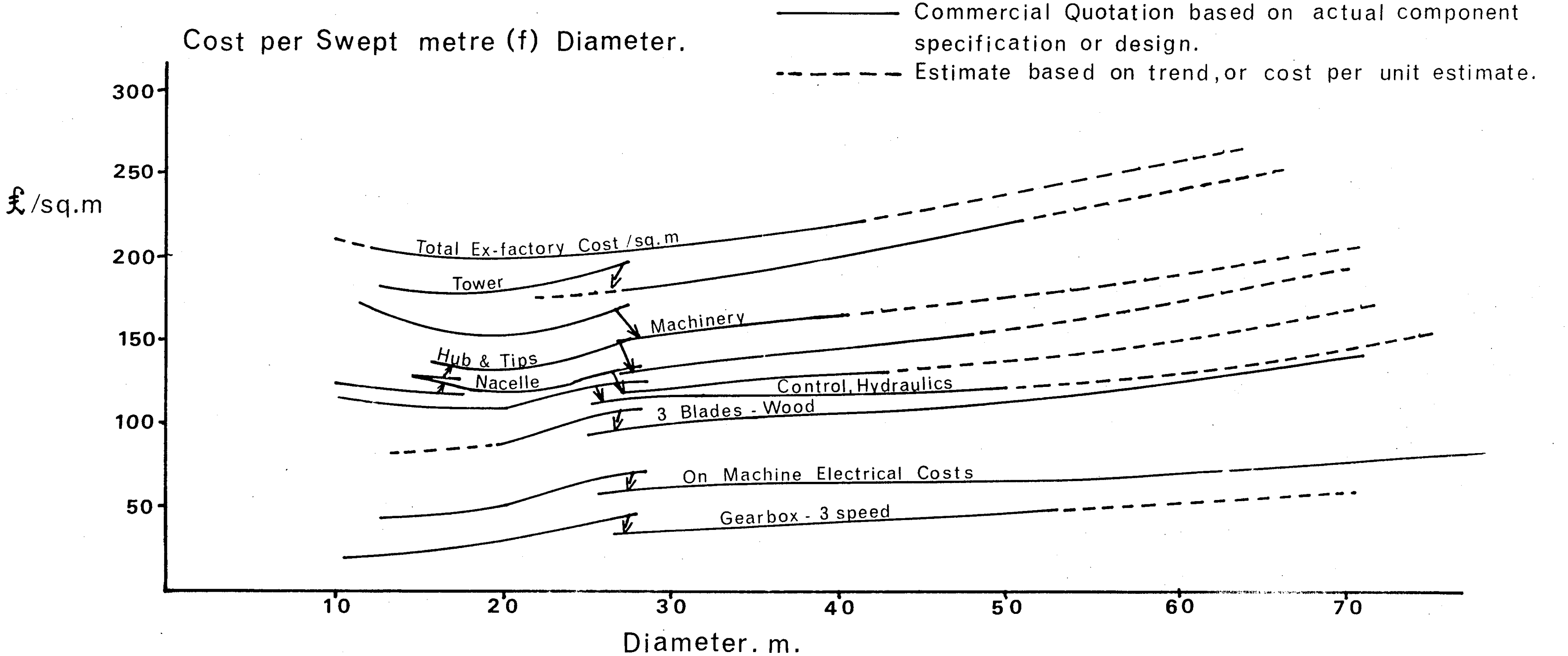


Total Electrical Costs (f) Swept Sq.m
(October 1987)
Multi-Speed, Sound Attenuation
2·5 MW cluster capacity,
600 W/Sq.m
£
Cost /sq.m
90
80
70
60
50
40
30
Single Machine.
Total Costs. 2·5 MW
On Machine Costs. (Single or Multiple Machines)
10
20
30
40
50
60
70
Diameter. m

Figure 11f

Ex-Factory Costs of Commercial Machines (420W/Swept sq.m)

1987 - State of the Art Machines. (October 1987)



Assumptions: Batch production of 25 machines, excluding transport to site.
Direct costs of components include costs of labour.
Design tipspeed ratio of 6.
Transport and Noise Attenuation measures not included.
Tower costs based on upper trendline in 'Tower Weight (f) Swept Area' figure.

Figure 11g

analysis tradition. However, some of these lighter towers have had problems in service. Also Van der Borg's and Stam's data is deficient in experimental results at high wind speeds for which contradictory field results are available from DEF (1962). As it will take some while to get the established codes altered, the higher weight trend is entered on the state-of-the-art graph. Figure 11e.

'On-machine' total electrical costs fall from 15m diameter to about 25m diameter when there is a sharp rise in generator costs which inhibits a further fall in total, electrical, specific costs until from 35m to 45m diameter after which costs remain constant. See figure 11f. Figure 11g summarises wind turbine ex-factory state-of-the-art costs.

The question arises: ARE THESE CURRENT COMMERCIAL COSTS SUITABLE FOR USE IN OUR SURVEY?

No. They are deficient in three respects:

1. Site Wind Speed and Installed Capacity.

Wind speeds at 10m agl in the three classes of wind turbine site in Denmark are:

Class 0 - 1 Mean of 6.7m/s
Class 1 - 2 Mean of 5.8m/s Petersen (1984).
for which an average 420W per swept square metre has emerged as the favoured installed capacity.

Now the best Cornish sites, which are also those likely to be developed first, have wind speeds in the range 7.5m/s to over 8.5m/s at 10m agl and from 8.0m/s to over 9.0 m/s at hub height. An optimisation exercise showed that the maximum return on investment for these sites was achieved with a capacity of 520W/square metre, plus a two hour overload capability of 600W/sq m., see figure 11h. The capital costs of providing this capacity were added to current commercial costs for the purpose of this survey.

2. Blade Failures.

Conservatively designed rotors (with built-in redundancy) have demonstrated long lives. Gedser is now thirty years old and has run for about ten years. The wind turbines in one of the two Danish wartime wind electric

Return On Investment (f) Installed Capacity.

(October 1987)

17·5 m Ø. No sound attenuation

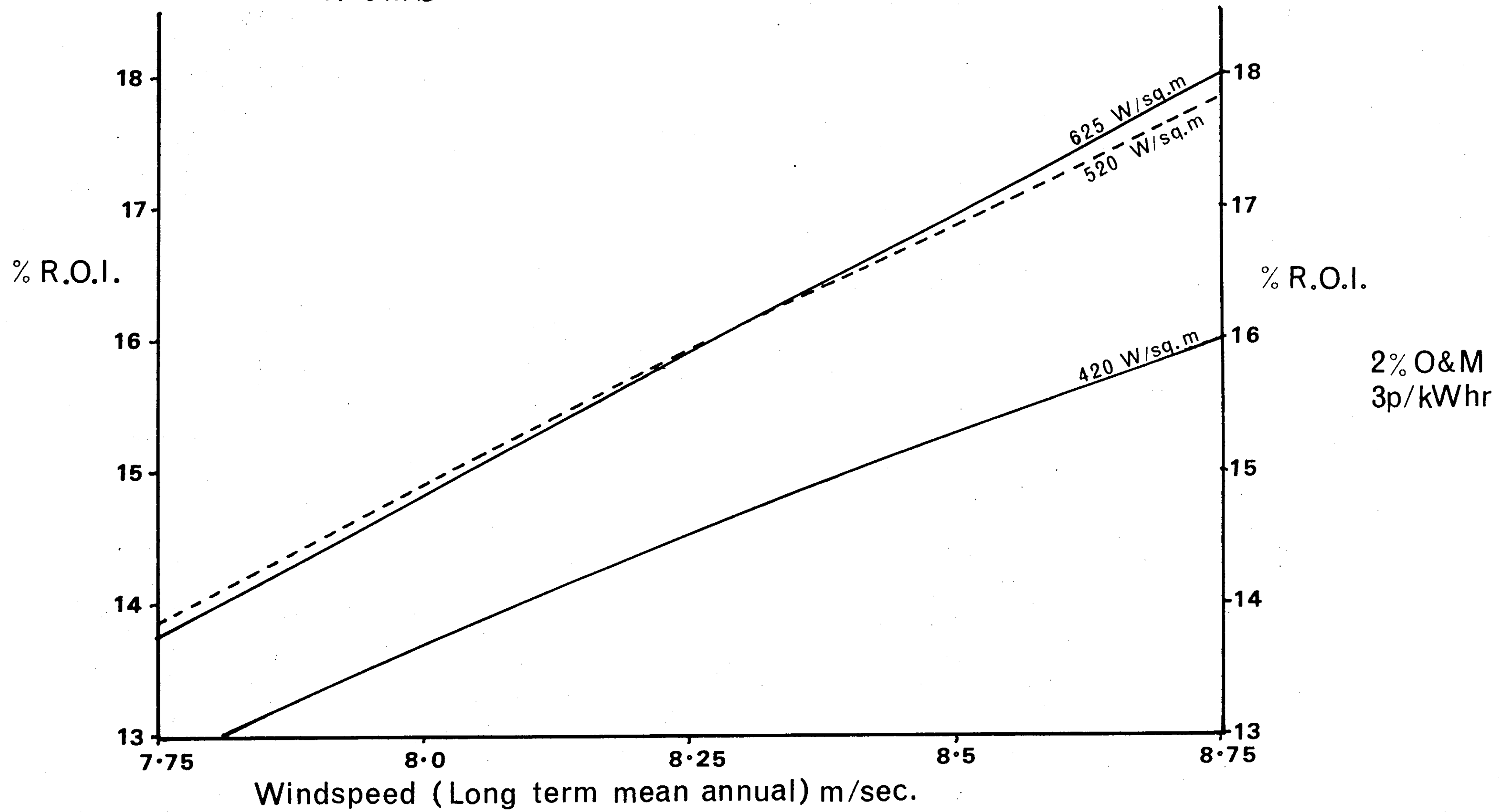


Figure 11h

utilities using Smidth machines mostly ran for about ten years and only fell into disuse on account of the change from a direct to alternating current distribution system. Westh (1975). Sir Henry Lawson Tancred's machine is 12 years old.

Windmatic emphasise that their early strutted and strapped rotors built in the late 1970's to 1982 still perform well, despite poor detailing on the spar aerofoil shell which led to early repairs of the polyester reinforced glassfibre.

To reduce costs and to give more operational flexibility in altering fixed blade pitch angles almost all manufacturers adopted wholly cantilevered designs from about 1982. The GRP blades used a root design on which development began in 1958 at the University of Stuttgart. This "Hutter root", was originally intended for glass reinforced epoxy materials, but the use of epoxies is subject to stringent health and safety controls in Denmark and possibly on this account polyester was used in its place on up to about 10,000 blades. Time has shown that they have a limited life of up to about five years and most blade manufacturers have abandoned this concept and started with entirely new designs.

For many reasons epoxy saturated wooden blades are attractive for wind turbines, but this raises the difficulty of using wood as an unsupported cantilever. Windmatic and others essentially ducked the issue and successfully transferred long established methods from boatbuilding. However, between 1977 and 1984 NASA, with the Gougeon Brothers, developed another innovative concept - the studded root. The application of this design has had some disasters and some successes, but the main problem is that it has been used on comparatively few machines for limited periods, and it cannot yet be certain that problems will not arise in early to midlife such as humidity induced dimensional changes at the root. Over the turbine's life the diameter of the blade root is expected to increase by about 3% as the wood approaches its equilibruim moisture content. This could strain or split the wood laminate when restrained by the cast iron hub, which is inflexible except for expansion and contraction caused by temperature changes. Any split could let in water and exacerbate the problem of the root wanting to expand.

To cover the extra costs arising from a more conservative blade design, or to provide a price weighting which would cover either more expensive blades built to higher quality assurance standards, or which issue from further research and development, or to provide some cover against early failure, an arbitrary sum of 20% has been added to blade costs for the purpose of this survey.

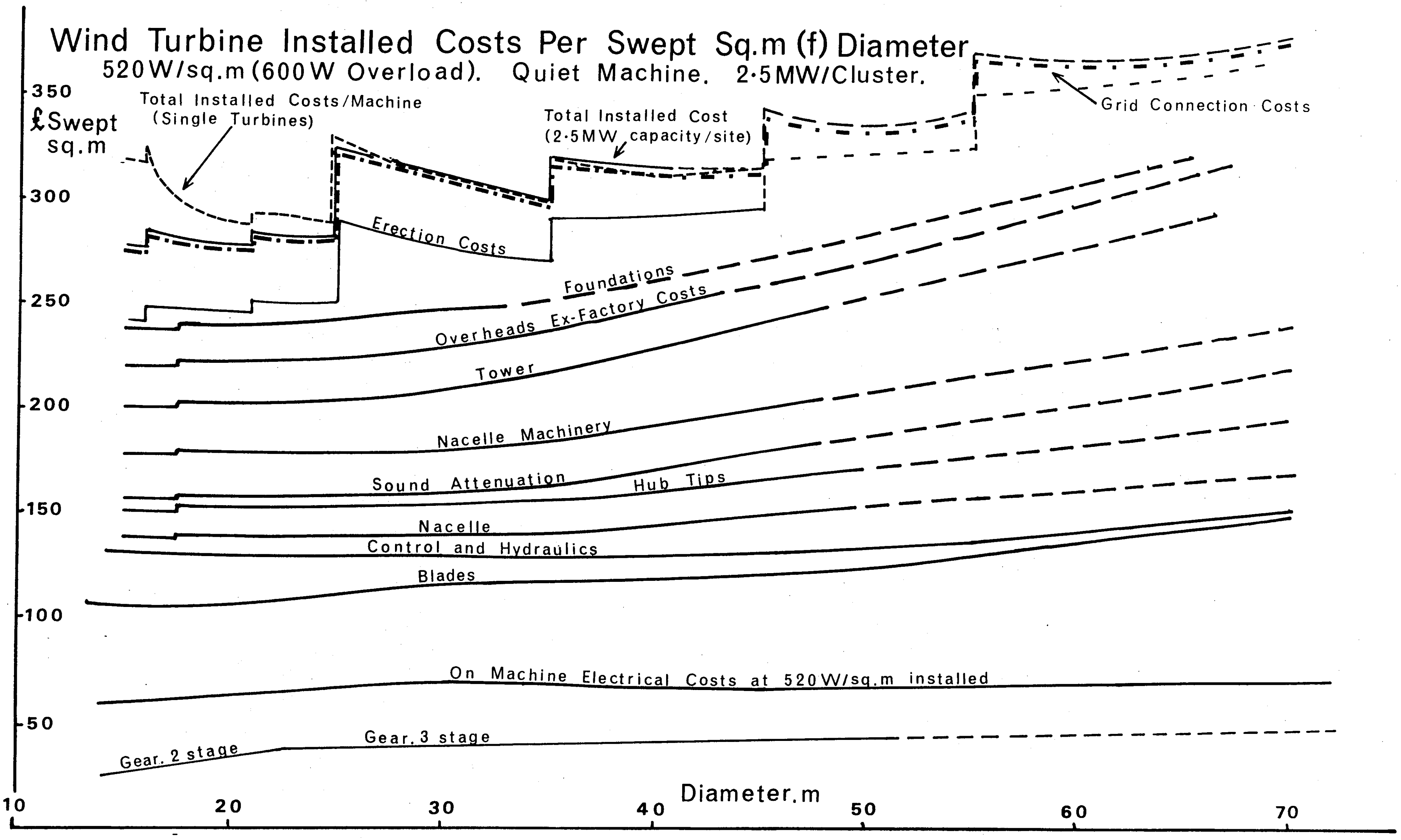

Wind Turbine Installed Costs Per Swept Sq.m (£) Diameter
520W/sq.m (600W Overload). Quiet Machine. 2·5MW/Cluster.
£Swept sq.m
350
300
250
200
150
100
50
Total Installed Costs/Machine (Single Turbines)
Total Installed Cost (2·5MW capacity/site)
Grid Connection Costs
Erection Costs
Foundations
Overheads Ex-Factory Costs
Tower
Nacelle Machinery
Sound Attenuation
Hub Tips
Nacelle
Control and Hydraulics
Blades
On Machine Electrical Costs at 520W/sq.m installed
Gear. 2 stage
Gear. 3 stage
Diameter.m
10
20
30
40
50
60
70

Figure 11i

3. Extra Costs Of Sound Attenuation

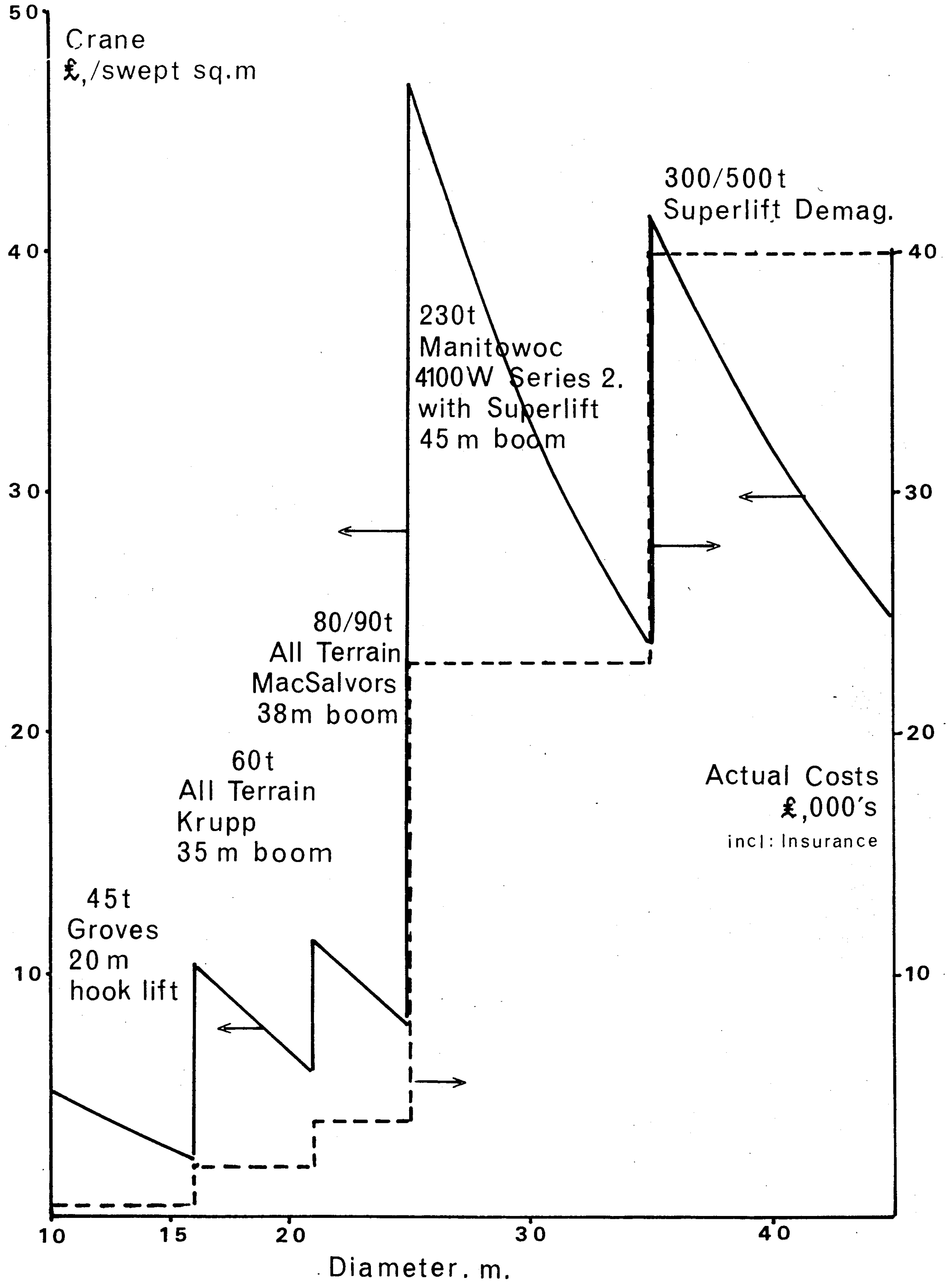
Costs arising from the measures needed to achieve the noise targets listed in Chapter 3 have also been added to turbine costs.

Revised Installed Capital Costs For Quiet Machines

Ex-factory turbine costs with the above additions are shown in figure 11i. Tower costs are based on the upper trend in figure 11e.

Actual foundation costs were available up to 25m diameter and erection costs for Cornwall were obtained by getting quotations from two crane companies for insured lifts up to a diameter of 45m. These costs agreed with those quoted by turbine builders. Erection costs have a marked effect on turbine installed costs. When, for example a turbine needs erection for which the only available crane size is substantially larger than that required, then cost per swept square metre suddenly rises and this is the explanation for the saw tooth pattern in the figure 11j. If further optimisation of crane/turbine matching is achieved, this will lower the peaks on the graph, but will not affect the troughs. It should be emphasised that beyond 45m diameter, crane and erection costs could not be obtained without substantial design and engineering studies. Hau (1984) points out that erection costs rise very sharply beyond this point and the estimated graph which follows the trend line may underestimate real costs. It was assumed that tracking would be hired to assist with the access for machines of over 25m in diameter. For the larger size of turbine, cranes would have to travel from SE or NE England. Therefore, Cornwall is disadvantaged in this respect. The smaller turbines could be erected with locally sourced cranes. Multiple lifts for machines erected in clusters would further reduce specific costs. Tracking or temporary roads and special lifting pads are not required for machines of less than 25m diameter.

On the graph of figure 11k, average values of mean grid connection lengths were entered from the variable costs of all 1511 sites. Trenching costs assumed that no hardrock and blasting was necessary for the cable laying and no allowance was made for upgrading the existing 11kV conductors from alloy to copper. It was assumed that wind turbine capacity would be installed up to the limit of the existing three phase overhead system (3MW) and up to the operational transformer capacity at the nearest 11/33kV substation and it was assumed for the purpose of this study that little further cost was incurred in reinforcing the system. It was found that if a cluster was sized to require a 33kV



Erection Costs (f) Diameter

Figure 11j

Quiet Wind Turbine, Installed Costs Per Swept Square Metre (f) Diameter, Normalised To Common Energy Capture In Respect Of Shear And Array Losses.

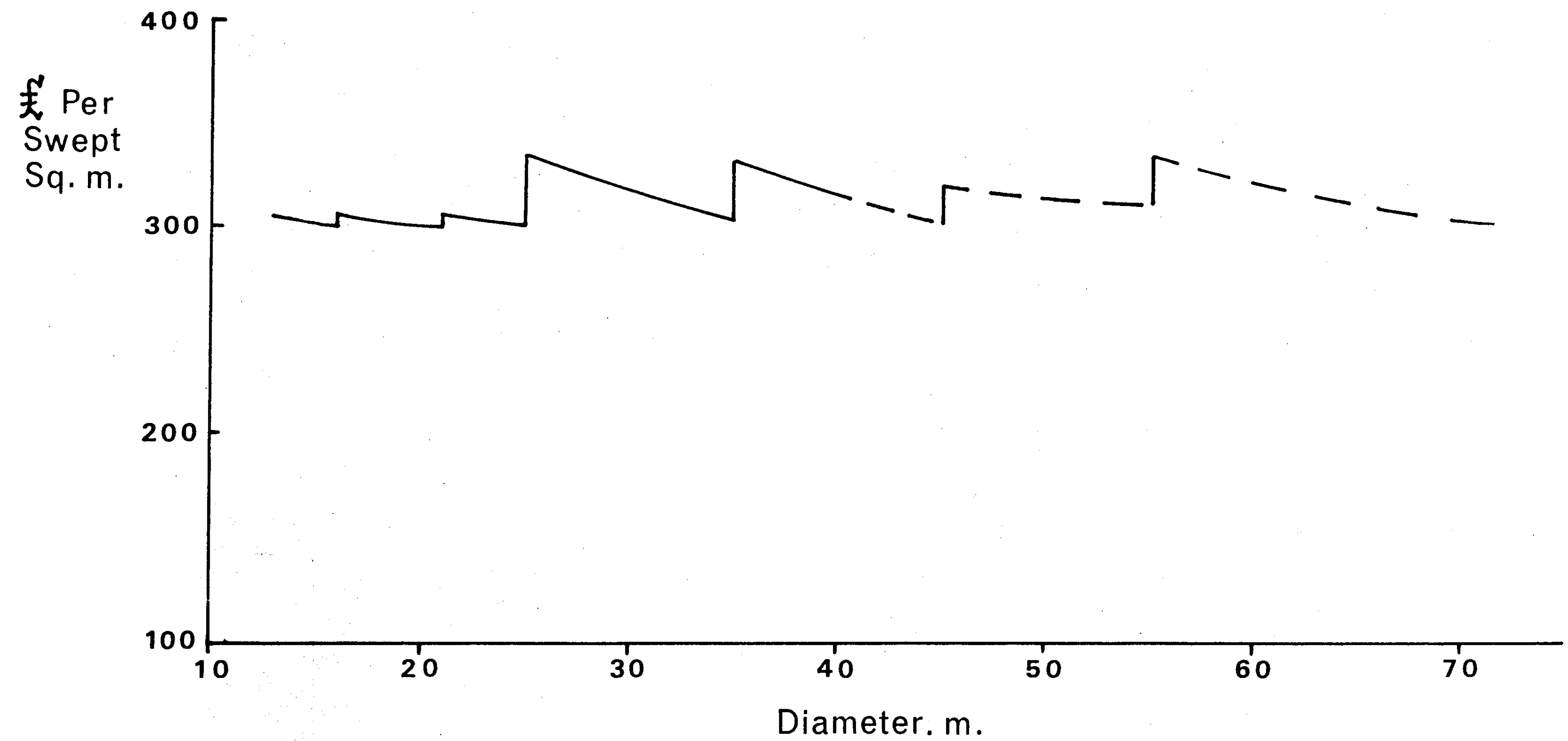


Figure 11 k

connection then kWhr costs rose by about 0.3p kWhr. There are only two or three sites in Cornwall which are large enough to need a 33kV link so this issue hardly arises and 11kV connection is assumed throughout.

11.4 Wind Turbine Capital Costs: The Results

The cheapest installed costs for single machines occurred in the 17.5m to 25m diameter range and averaged £295 per swept square metre (Oct 1987). This is equivalent to £567 per kW installed.

In addition to the costs for the single largest machine per site there are also shown the costs for installing the maximum capacity on sites which are over 350m to the nearest habitation by using clusters of machines. Costs were based on the provision of 2.5MW per cluster and costs then averaged £280 per swept square metre (Oct 1987) or £538 per kW for machines up to 25m diameter, rising beyond £300 per square metre above this size.

Installed Turbine Costs Corrected For Shear And Array Losses.

The site specific cost of energy for every potential site takes account of the effect of array losses and wind shear. To show the effect of these two factors on installed machine capital costs figure 11i was normalised to a common energy output by incrementing or decrementing the capital cost to correct it for array loses and the effect of shear. Array efficiency was determined by:

(Number of machines) Exp 10 -0.02

Also, it was assumed that the lighter tower was used throughout the range of machine sizes. The result, in figure 11k indicates that normalised capital costs vary little over the range of machine sizes considered. A corrected cost of £300 per swept square metre, or £576 per kW is indicated when the capacity of the relevant crane size is matched by the maximum diameter machine which it can lift. There is a high confidence level for achievable costs up to about 40m diameter beyond which there are numerous uncertainties.

11.5 Wind Turbine Capital Costs: Conclusion

When machines are compared on the cost of the energy which they produce, then there does not appear to be a strong case for choosing one size of machine in preference to another. Other factors such as commercial risk, cluster reliability as a function of machine number, the maximising of output per sq. km. of land surface and above all, environmental factors, will have a much more decisive role in determining the best size(s) of machine to use.

Wind Turbine Costs References

BOYLE, G. (1988)
"Economics of scale in the UK wind energy research, development and demonstration programme." Journal of Interdisciplinary Economics, Vol 2 pp 271-285.

DANISH ELECTRICITY UNDERTAKINGS. (1962)
"Development testing and operation of a 200kW wind power station in Denmark." Report of the Windpower Committee of the Association of Danish Electricity Undertakings. Published by ERA, Trans/IB 2158. Copenhagen.

DIVONE, L.V. (1982)
"Technical and economic progress in the development of wind power." Procs. of 4th Int. Symp. on Wind Energy, Stockholm.

ELECTRICITY COUNCIL. (1985)
"Recommendations for the connection of private generating plant to the electricity boards' distribution system." Engineering Recommendation G59 June.

ELLIOTT, D. E. (1975)
"Economic wind power." Applied Energy Vol 1, pp 167 - 197.

FOLLINGS, F.J., RENAUD, J.E. (1986)
"The market of wind turbines in the European communities in relation to the state of the art of WECS technology." Procs Of European Wind Energy Assoc Conference pp 605-609, Rome 7-9 Oct.

GOODMAN, F.R. Jr (1985)
"Price targets for wind turbines in utility applications." Electric Power Research Institute, Palo Alto, California.

GIPE, P. (1985)
"An overview of the US wind industry - the road to commercial development" Alternative Sources of Energy Vol 75, pp 25-27.

HARRISON, R., JENKINS, G.T. (1987)
"Parametric cost modelling of wind energy conversion systems." pp 259-264 Procs 9th BWEA Conf. 1-3rd April.

HAU, E. (1984)
"What is the most economical size for a large wind power plant?" Procs: of European Wind Energy Conference, pp 820-825 Hamburg, 22-26 October.

IGRA, O. (1979)
"Cost effectiveness of vortex augmented wind turbines." Energy. Vol 4, pp 119-130.

LJUNGSTROM, O. (1977)
"Neuentwicklungen von windturbinen". pp 165-186 in Energie vom Wind, Procs: of Conference held at Bremen 7 - 8 June 1977, pub. by Deutsche Gesellschaft fur Sonnenenergie e V.

MILBORROW, D.J., INVERNIZZI, GRASTRUP, H. and OVERDIJK, J. (1986)
"Electricity from the wind - current prospects." Procs: European Wind Energy Assoc. Conf. pp 65-73, Rome, 7-9th October.

MUSGROVE, P J.
"The economics of existing wind turbines in the size range 10 to 100 metres diameter."

PEPPER, J. C. (1984)
"Wind farm economics from a utility perspective." Pacific Gas and Electric Company, California.

PETERSEN, H. (1984)
"Simplified laws of similarity for wind turbine rotors." Riso-M-2432. May.

SELZER, H. (1984)
"Results of the assessment study of the technical/economic prospects for wind energy in the European countries." Procs: European Wind Energy Conference, Hamburg, pp 18-22, 22.26 October.

SOAN, B. (1984)
"Review of cost trends in wind turbine construction" by W.S. Atkins Group Consultants WESC p9, 52019 03, 1985 and private communication with B. Soan.

TAYWOOD ENGINEERING et al. (1985)
"Report on offshore wind energy assessment phase IIB Study." Dept. Of Energy Report 014V/OW/102.

VAN DER BORG, N.J.C.M.; STAM, W J. (1986)
"Axial thrust measurements on wind turbine rotors and comparison of measured data with guidelines." pp 391 - 395 Procs: European Wind Energy Conference, Rome. October.

WESTH, H.C. (1975)
"A comparison of wind turbine generators." pp 156 - 161, Proceedings of the Second Workshop on Wind Energy Conversion Systems, Washington 1975, published by the Mitre Corporation.

WILLIAMS, G.J. (1982)
"Report for ECLP & Co Ltd 1978." Updated 1980 and 1982.

WILSON, R R., JAMIESON, P., McLEISH D A. (1982)
"The effect of rotor diameter, tower height and generator rating on the economics of wind energy." 4th BWEA Conf. Procs. Cranfield.

12. ENERGY INCOME AND RETURNS ON INVESTMENT

Abstract

The kilowatt output as a function of instantaneous wind speed for the Windpower & Co machine at Treculliacks was applied to the St. Mawgan frequency distribution curve to get an annual output. The shape of the St. Mawgan frequency distribution curve was found to be representative of most Cornwall turbine sites.

Operating and maintenance costs were found to be 2% of total capital cost and the appraisal method currently used by the utilities was applied to every site.

Using a five percent discount rate and a twenty five year life, 64% of the prospective sites in Cornwall were viable. However, if diesel backup is provided for the wind turbines then the extra value of its output to an Area Board raises the percentage of viable sites to 96%.

12.1 Energy Income And Returns On Investment: The Method And Work Done

The annual kWhr output for the wind turbines in Cornwall was determined from the graph of instantaneous output at the electricity meter as a function of instantaneous wind speed at hub height for the author's turbine at Treculliacks. The data for this graph was collected according to the method recommended by the International Energy Agency, 1982.

The frequency duration curve for St Mawgan was obtained from the Meteorological Office data. This is representative of sites on the coastal platform land of Cornwall. The frequency duration curve was also obtained for a high level, high wind speed, inland site at the centre of one of the granitic massifs. This was compiled from one year of wind speed readings made on two anemometers and stored on Second Wind's AL2002 data recorder. The sampling rate for this data was once every two seconds.

In order to see if the distribution of hours at various wind speed bands was similar for these geographically different sites we need to reduce the data to a single number per site so that they can easily be compared. This can be done by finding the two constants c for scale, and k for shape in the Weibull distribution:

$$f(u)=\frac{k}{c}\left(\frac{u}{c}\right)^{k-1}\exp\left[-\left(\frac{u}{c}\right)^{k}\right] \quad k>0,\ u>0,\ c>1$$

Where u = wind speed.

The data for St Mawgan and the high level site were reduced to a single Weibull shape function (k) number. These numbers were found to be very similar. Therefore, the average of this Weibull shape factor was then applied to all Cornish sites to get the number of hours per annum for which each band of wind speed persisted. This was then matched to the performance data for the author's turbine to give an annual output in kWhrs per square metre swept by the rotor. In this way the output could then be easily applied to turbines of any size by making the assumption that they would have the same efficiency as the author's machine. It was assumed that the hub height wind speed pertained right across the rotor and the marginal difference arising from the almost vertical shear profile was ignored. Variable pitch turbines and machines larger than the author's and operating at a higher Reynolds number could be expected to have slightly improved specific performance, but this too was ignored for the purpose of this survey.

Annual operating and maintenance costs, insurance, rates (local taxation) from the Electricity Supply Industry's formula, spares and oils, site rent and units lost due to unplanned downtime were entered as 2% of the total cost of the installation. This figure is derived from the operating experience of the author's machine. The life of the installation was assumed to be 25 years. By applying the 5% discount rate then the cost per kWhr was found from:

Cost per kWhr = (Capital Cost x .091)/ Annual Predicted Output in kWhrs.
(BWEA, 1987)

Turbine installed capital costs for quiet machines were derived from chapter 11. Hub height wind speeds for each site were converted to annual output and the above formula was then used to get a cost of energy per kWhr.

Commercial organisations supplying electricity to the grid would use different financial criteria, but since at the time of writing, institutional impediments prevent all operators except the utilities from building substantial commercial wind installations, then only the utility method of appraisal is relevant.

12.2 Energy Income And Returns On Investment: The Results

The value of wind produced electricity to the CEGB (private communication, 1987) has been given as approximately 2.2p/kWhr plus about 0.3p kWhr allowance for capacity when the latter is based on the load factor. Therefore, a wind energy cost of 2.5p/kWhr or less is assumed to be economic when the above assessment method is used.

The following table is compiled from the analysis of sites where the largest single, quiet machine is installed at each site.

Table 12.1 Cost Of Energy (f) Number of Sites

Cost of Energy	Number of Sites
Less than 1.75p per kWhr:	92
1.76p to 2.00p	261
2.01p to 2.25p	346
2.26p to 2.50p	275
2.51p to 2.75p	249
2.76p to 3.00p	142
3.01p to 3.25p	58
3.26p to 3.50p	26
Over 3.51p	62

12.3 Energy Income & Returns on Investment: Value Of Wind Energy With Firm Backup

When the CEGB is providing virtually all the generating capacity for England and Wales then it is reasonable to allow capacity credit on the basis of the wind turbine's load factor as the Board does not face any penalties when wind is not available, but instead uses its other plant to make up the deficit. Therefore, there is no justification for the Board to provide any local backup in the form of diesel, gas or dual fired engine driven generators to provide relatively firm output at the site of the wind turbines. It is uncertain if after privatisation the new terms for supply will maintain this situation.

Any other generator faced with a contractual duty to supply a certain load on demand has either to provide back-up generation or purchase this from another party. This is reflected in the credit earned on firm and non-firm supplies by different operators in 1987:

Table 12.2. Value of Firm And Non-Firm Supplies.

CEGB	
2.2p/kWhr for energy, 0.3p/kWhr for capacity:	2.5p/kWhr
Independent Cogenerator	
Non firm supply from wind, 8.5m/s site:	1.63p/kWhr
Non firm supply from wind, 7.0m/s site:	1.27p/kWhr
Wind output from 8.5m/s site plus 90,000kWhrs from diesel backup:	2.33p/kWhr
(SWEB, 1987a)	
Area Board	
Firm supply as from wind/diesel:	3.424p/kWhr
(SWEB,1987b)	

Local, firm supply for an Area Board has the further advantage of delaying or eliminating the need to uprate substations and overhead lines if the wind turbines are located in an area where there is a growth in demand.

There are many possible strategies which an Area Board could use in running the diesels. One of these would be to operate them at times of maximum system demand and no wind. Maximum system demand almost always occurs during week days between 7.30am and 8pm in December and Janauary. Maximum demand is currently monitored by the CEGB during three hundred half hour periods.

If we assume that wind output is available for about one third of these occasions we are expecting the diesels to generate about 200 times per annum.

For example, consider a typical cluster with 15 x 150kW machines on an 8.5m/s site backed by a 2.25MW diesel. (From the capacity and tariff point of view it will often pay to install the largest standby that the 11kV distribution network can normally accommodate. That would be 3MW). Then:

Table 12.3. Output From A Wind/Diesel Cluster

Output of 2.25MW of wind turbines:	6,875,000kWhrs
less 3.5% unplanned downtime say	240,000
Net output:	6,635,000
Diesel engine output, 200 x 1/2 hr:	225,000
Total output:	6,860,000kWhrs
Saving of transmission losses at 4%	274,400kWhrs.

The first impression of the concept of wind/diesel located close to demand on a strong, interconnected grid is that fossil fuel usage will increase. This is not so. Cornwall is situated so far from its current sources of generation that for every 100 kWhrs consumed in the county, 104 kWhrs need to be generated.

By siting the wind/diesel clusters very close (<5kM) to existing load centres, a 4% transmission saving is achieved. The 4% is based on the entire output because that figure represents the total generation offset in the country as a whole. This is justified on account of the very low value that an Area Board places on wind output which is not relatively firm. Without the diesels none of this capacity could be considered by an Area Board.

Now 4% of the output from the example tabled above is 0.04 x 6,860,000 = 274,400 kWhrs which exceeds the diesel generated units of 225,000 kWhrs. Therefore overall, local wind/diesel reduces total fossil fuel usage in the county by 100.7% of the consumption that would have occurred,if the wind diesel option had not been used!

For the Area Board the output from wind/diesel installations can be treated much like a conventional power station yielding firm capacity. Indeed, the large number of distributed sources would be very firm since the probability of a multiple failure would be low. The possibility of using existing diesels already installed in Cornwall was also explored. Their aggregate capacity was just under 30MW, but most of these units were unavailable for this sort of scheme because of various institutional problems.

Another potential benefit from the wind/diesel scheme would involve placing the gas or diesel engine on the same 11kV feeder as the wind turbine cluster, but siting it close to a heat load. In this case, longer hours of running would be justified, both financially and in terms of fossil fuel resource depletion, by using the waste heat in local, combined heat and power schemes. For houses which already have oil fired central heating the existing radiators could continue to be used and the boiler would act as backup to the oil or gas engine. The fuel normally used directly in the domestic heating systems would simply be diverted to the gas or diesel fired generator.

A desirable goal would be for the diesels to have a fuel which came from a renewable source, such as methane from landfill gas, kelp processing, sludge burning with oxygen or some other biomass source. The methane would need to be converted to methanol for convenient storage and transport.

12.4 Energy Income & Returns on Investment: Wind/Diesels And Their Influence On Viability

When the extra capital and operating costs of wind diesels are allowed for and the increase credit per kWhr is applied, the number of sites which are viable rise from 974 to 1451. This reperesents an increase from 64% to 96% of all sites. The wind speed threshold drops from about 7.25m/s to 6.625m/s when measured at twentyfive metres above ground level.

12.5 Energy Income & Returns On Investment: Conclusion

The table shows that 64% of the sites are judged to be economic when using 5% discount rate and 25 year turbine life. This percentage of sites which are viable to an Area Board rises to 96% when the wind turbines have firm backup from diesel generation.

With these result from chapters 11 & 12, the purely physical aspects of turbine siting now have the added measure of financial viability. The following chapter further refines the selection of prospective sites according to their local landscape features.

Energy Income & Returns on Investment References

BRITISH WIND ENERGY ASSOCIATION (1987)
Windpower for the UK. A position paper published by the BWEA, 4 Hamilton Place, London W1V OBQ. 1987.

FRANDSEN S, TRENKA A R, PEDERSEN B M. eds. (1982)
Expert group study on recommended practices for wind turbine testing and evaluation: 1 Power Performance Testing. Submitted to the Executive Committee of the International Energy Agency Programme for research and development on Wind Energy Systems. 1982.

SOUTH WESTERN ELECTRICITY BOARD (1988)
Purchase Tariff MPTA 88.
Supply Tariff A MSTA 88.

Annual Report 1987.

13. THE SELECTION OF POTENTIAL WIND TURBINE SITES

Abstract

Over 3500 potential sites for wind turbines were discovered. About 1000 sites were eliminated due to "site blockers" such as being too close to an airfield, town or village, being situated in a nature reserve, site of special scientific interest etc. The remaining sites were reduced to 1511 prospective turbine locations after allowance had been made for the avoidance of radio frequency interference.

13.1 The Selection of Potential Wind Turbine Sites: Method

From a detailed examination of the 1:25,000 scale maps of Cornwall, over 3500 potential wind turbine sites were discovered. Sites were then rejected if any one of the following conditions applied:

Within 200m of any habitation
Within 1000m of any village (to avoid the expense of rectifying television reception problems at a large number of dwellings)
Within 2500m of any town (to be beyond the ultimate blade throw and glide distance)
Within 5000m of any airfield (CAA and MoD requirement)
In a site of Special Scientific Interest
In a National Nature Reserve
Within 50m of an Ancient Monument
Within 25m of an adopted road
Within 100m of a 132kV or 400kV transmission route
In water or wetland, in reeds, marsh or saltings
If a war memorial would be dominated by the wind turbine
Within six diameters of another turbine
Where the windflow to the rotor is likely to be seriously impeded over any 60 degree or greater arc save betwen N and ESE
On a cherished hilltop
In a field where a hedge, confluence of hedges, drains or unused land can be used instead
Where the landowner has either refused permission for wind turbines or where the land tenure is known to be complicated
On land owned by the National Trust
Over 1km from an access track or where access is seriously impeded by cliffs and/or marsh

This reduced the gross number to 2220 sites. There was a further reduction to 1511 sites when account was taken of radio frequency interference.

English China Clays International

In the late nineteen seventies there appeared to be a very attractive wind energy resource, probably exceeding 100MW in capacity, on English China Clays' land. This area also had some of the greatest separation distances in Cornwall. Here, there was already in place a comprehensive, privately owned, 11kV network, a single customer with a 40MW load and excellent wind speeds which were discovered in two measuring campaigns.

However, the subsequent development of microwave routes sterilised the majority of the best sites, and only two to three tips are likely to be available for development on a permanent basis.

13.2 The Selection of Potential Wind Turbine Sites: Conclusion

The gross number of sites in the county was reduced to approximately 43% of the total number when site blockers of various kinds were allowed for. The remaining 1511 sites are further analysed in the next chapter as a function of landscape designation and local landscape features.

14. ANALYSIS OF SITES

Abstract

The average separation distance from habitation was 327 m with a range of 200 to 800m. 37% of sites were in Class I landscapes (ie nationally designated Areas of Outstanding Natural Beauty); 19% were in Class II landscapes (A Cornwall County Council, not a national, designation of special landscape, historical or scientific value) and 44% were in non-designated areas. 92.5% of sites had adjacent downward slopes in two or more directions. 18% of sites were in agricultually "Less Favoured Areas". The average distance to the nearest interconnection point at the 11kV or 33kV network was 220m, but the average length of line needed for upgrading from single to three phase was 700m.

14.1 Analysis of Sites: Results

In the beginning there were about 3500 possible wind turbine sites, but this number was reduced by site blockers of various kinds to a total of 1511. These sites had the following characteristics:

Separation Distances From Habitation

The table shows the number of sites as a function of distance to the nearest habitation. The average separation distance is 327m and the largest distance is 800m.

Table 14.1 Distance To Habitation (f) Number of Sites

Separation Distance	Number of Potential Turbine Sites
Approximately 200m	347
201 - 250m	282
251 - 300	282
301 - 350	184
351 - 400	140
401 - 450	88
451 - 500	86
501 - 600	41
601 - 700	60
701 - 800	1

Table 14.2 Sites As A Function Of Landscape Classification Type

Landscape Classification		Number of Sites
Class I	Areas of Outstanding Natural Beauty	370
	Special Area of Great Landscape Value	192
	Class total:	562
Class II	Areas of Special Landscape Value	252
	Areas of Great Scientific Value	179
	Areas of Great Historic Value	4
	Cornwall Trust Conservation Site	6
	Local Nature Reserves	0
	Country Park	0
	Class total:	441
Class III	Non-designated land, class total	655
Class IV	Derelict or industrial land, class total:	8

These total 1666, not 1511, because some sites have multiple designations.

Table 14.3 Sites As A Function Of Agricultural Land Classification

Land Classification	Number of Sites
Ministry of Agriculture Land Grade 2	160
Grade 3	1005
Grade 4	210
Grade 5	105
Not applicable	31

Table 14.4 Sites In Agriculturally Less Favoured Areas

Total number of sites in LFAs:	271
Sites not in LFAs:	1240

Table 14.5 Sites As A Function Of Hill Top Position

Sites surrounded by no downward slopes:	14
Sites with one downward slope:	99
Sites with two downward slopes:	458
Sites with three downward slopes:	426
Sites with four downward slopes:	514

62% of sites are on hills or ridges.

Table 14.6 Sites As A Function Of Site Promotors

1. Sites with an open aspect and uninterrupted windflow to them from all directions save for any 60 degrees included between north and east-south-east: 1487 sites

2. At or near an existing wind pump: 81 sites

3. Close to a factory, industrial estate or mine providing that other site blockers do not apply: 9 sites

4. Less than 50m from an existing 11kV or 33kV overhead line: 675 sites

5. As a diversion from existing ugly development such as, mineral waste tips, radio towers etc: 8 sites

6. Where other existing redundant structures could be removed and replaced by a wind turbine: 10 sites

7. On disused airfields: 3 sites

8. Derelict or unused land, near a quarry, sandpit or refuse tip: 193 sites

9. In a hedge, at a confluence of hedges, ditches, banks, or tracks, in bracken, scrub, rough grassland, on heath or on rock outcrops: 1247 sites

10. As a marker for a tourist attraction such as Dairyworld, or Lappa Valley railway providing other criteria are met: 13 sites

11. In an agriculturally "Less Favoured Area": 244 sites

12. Near a busy road(s) when traffic noise will mask turbine noise for part of the time: 1 site

Table 14.7 Sites As A Function Of Distance To The Neighbouring Turbine

If each site is developed with a machine of a diameter of one tenth the separation distance to habitation, and if the neighbouring site turbine is placed at six or more diameters distance, then:

46% of turbines suffered no interference within 15 diameters,
24% were in sets of mutually interfering machines at between 6 and 15 diameters apart.
20% were in sets of three machines at 6 to 15 diameters.
4.7% were in sets of four machines at 6 to 15 diameters
1.1% were in sets of five machines at 6 to 15 diameters
4.2% suffered marginal interference beyond 15 diameters.

Table 14.8 Wind Turbine Sites As A Function Of Distance From The Existing Electricity Distribution System

Distance To Nearest 11kV Overhead Line	Number of Sites
Less than 50m	675
51 to 150m	148
151 to 250m	188
251 to 350m	160
351 to 450m	123
451 to 550m	83
551 to 650m	44
651 to 750m	29
750 to 1000m	34
1000 to 1500m	16
1500 to 2500m	11

The average distance to the nearest overhead line is 220m

Distance Over Which Single To Three Phase Upgrading Is Required.	Number of Sites
Up to 250m	485
251 to 500m	389
500 to 750m	175
751 to 1000m	137
1000 to 1250m	51
1251 to 1500m	72
1501 to 1750m	52
1750 to 2000m	42
2001 to 2500m	46
2501 to 3000m	19
Over 3001m	43

The average distance for upgrading to three phase is 700m.

14.2 Analysis of Sites Conclusion

This Chapter concludes the selection and analysis of all of the prospective sites' characteristics.

This provides the data base on which:

(a) various policies for the selection and installation of different types and sizes of wind turbine can be tried out in order to find which approach achieves the greatest resource. THE ANSWER TO THIS QUESTION IS THE CENTRAL ISSUE OF THE STUDY.

(b) various landscape planning policies can be assessed to see how these affect the size of the resource.

15. THE ACHIEVABLE RESOURCE

Abstract

In the beginning there were over 3500 potential sites in Cornwall, but these reduce to 1511 after taking account of the various site blockers. The question arises - what percentage of these sites could be developed in practice, and what is the achievable resource? How would the type of machine(s) chosen to develop the resource, and the disposition of those machines in the landscape, affect the size of that resource? These two issues are considered in turn:

1. The type and size of wind turbine favoured by the operators, and the preferred layout for that machine in any windfarm.

Here it was found that the achievable resource for a given, fixed number of sites varied inversely with individual machine size down to about 15m diameter, below which various factors tended to make the resource less economic. The gross resource in Cornwall for state-of-the-art machines was negligible, primarily on account of the quietness of the countryside and the existing noise standards of the District Councils. However, this study found that it was possible to reduce total noise levels at affected properties by about 13dB(A) if machines in the 15m to 22m diameter range were specifically designed and built for that purpose. No such machines exist at present. With these quiet machines in this size range the resource rises to 1535MW for all the sites and pro rata for any proportion of the total number of sites.

Windfarms generally had small capacities of up to 2.5MW suitable for connection to the 11kV network. If operators specified minimum capacities of say 7.5MW which would be appropriate for connection at a higher voltage the resultant resource was negligible. Windfarm size and layout needs to respond to rural settlement patterns.

2. Landscape Planning Policies And The Issue Of Saturation

If the County Structure Plan excluded wind turbines from Areas of Outstanding Natural Beauty and from small sites then the viable resource for quiet machines falls to 500MW. If Class 2 landscapes ie Areas of Great Landscape Value, Great Historic Value or of Great Scientific Interest are also excluded then the resource drops to about 280MW.

Strict environmental criteria could be satisfied at individual sites in achieving the above resource. However, one can anticipate rising opposition to the idea of many hitherto empty hill tops being given over to wind generation. It is only possible to guess the degree of saturation beyond which there will be strong resistance to further development and uncertainty on this issue compromises the integrity of any survey of the potential wind energy resource. Given that medium size wind turbines can be seen for up to seven kilometres from any site, then in this report a range of only 1% to 10% of developed sites is considered as a practical percentage of the gross number of vacant sites in Cornwall (that is as a percentage of the total number of sites which is 3500). 10% saturation yields 500MW. This is the same figure as that which results when one excludes the AONBs. For the purpose of this study, 500MW is adopted as the maximum <u>achievable</u> resource in Cornwall.

15.1 The Achievable Resource: The Problem

The achievable resource is conditioned by two major constraints:

1. The type and size of plant which the utility (or other operator) chooses to purchase and install, and the preferred disposition of those machines, i.e. whether they are in groups each of some minimum capacity, or if they are installed singly.

2. District Council planning consents for turbine installation. Here, it is only possible to present the resource in terms of the total number of viable sites, their characteristics as described in the tables above and as a function of the landscape designation given in the County Structure Plan.

15.2 The Achievable Resource: The Aim

The aim is to see how the wind energy resource is affected by various wind turbine designs, plant purchase options and various District Council planning policies.

15.3 The Achievable Resource. Methods, Work Done And Results

15.3.1 Plant Purchase Options And Their Effect On Total Resource.

Each of the 1511 sites was assumed to be developed using different plant purchase options and environmental standards:

Table 15.1 Resource As A Function Of Turbine Size And Type

	Resource
Multimegawatt Machines For Cornwall. The operator specifies a 2.5MW machine with a nominal 800m separation zone. Environmental standards listed in chapter 9 are not maintained:	2.5MW
Multimegawatt Machines For England and Wales. A map study of all of England and Wales outside a Areas of Outstanding Natural Beauty revealed 457 sites each with a 800m separation zone of which 297 had severe access difficulties, or other problems, leaving a net resource of 160 sites. Environmental standards listed in chapter 9 are not maintained:	400MW
State-of-the-Art Machines For Cornwall. On each of the 1511 sites we install the largest standard machine that can be accomodated and satisfy the siting criteria listed in chapter 9:	Negligible
State-Of-The-Art Machines Of A Single Size. A single size of machine is adopted for the Cornwall sites and the siting criteria of chapter 9 are satisfied:	Negligible
Largest Quiet Machine Per Site. On each of the 1511 sites there is installed the largest, single, quiet machine that can be accommodated and satisfy the siting criteria listed in chapter 9:	360MW
A Standard Size Of Quiet Machine Is Used. The siting criteria of chapter 9 are satisfied. A standard size of machine is used as the single machine on all sites:	

15m diameter	166.2MW	24.2m	82.0MW
17.5m	169.3MW	27m	72.3MW
18.2m	142.0MW	33m	79.7MW
20.0m	117.0MW	44m	1.5MW
22.0m	100.0MW		

Table 15.1 (cont)

Windfarms Of 25 Off, 30m Diameter Machines. Standard machines are used and siting criteria of chapter 9 are not satisfied. Instead a 300m separation zone between machines, and between machines and buildings, is specified.	53.1MW
Windfarms With A Minimum Of Twelve, 30m Machines. Standard machines are used and the siting criteria of chapter 9 are not satisfied.	114.7MW
Maximum Capacity Per Site, Quiet Machines. The operator specifies that he wants themaximum conceivable capacity per site, that the environmental standards of chapter 9 are to beretained, that the size per machine is not less than 15m diameter, 110kW installed, but otherwise, machine size is to be iterated to derive maximum capacity and this capacity is to be adjusted to take account of cluster losses. The sum of noise at surrounding properties is to be less than 20dB(A).	1535MW

Due to the very substantial amount of work needed in iterations to maximise the resource on each of the 1511 sites the method used consisted of modelling the sites in each "distance to habitation" band in order to find the optimum combination of machines and sizes. Then, for all the actual, mapped sites one tenth in each "distance to habitation" size band was examined on the map to see how many machines could be accommodated and retain the environmental standards listed in chapter 9. The average number of turbines per site was then found for each size band. Finally the ratio between this average number from the real sites was compared with the number of turbines per site from the modelled sites and the resultant model/map ratio was then applied to all the real sites.

Results: The Effect Of Plant Purchase Options

For any given, fixed number of available sites it was found that the wind energy resource is inversely proportional to individual turbine size. However, when the cost of energy was taken into account, machines of about 15m diameter or less became sub-optimum due to:

- increasing specific array loses,
- the need to specify a longer tower than the economic minimum in order to raise the rotor up above the knee in the shear profile curve, (See chapter 2)
- slightly increased cabling costs for typical windfarm layouts

By the methods used, the range of optimum machine sizes came out at between about 15m and 22m diameter, with the most resource arising in the 17m to 19m diameter range. To check this finding, these conclusions were not revealed to a second investigator - Dr Nevitt - who was asked to repeat the exercise from scratch. Virtually identical results were achieved:

Table 15.2 Resource As A Function Of Site Size For 15-22m Diameter Machines

Separation Distance	No of Sites	x Capacity of Machine	x Machines per site	= Total Capacity(kW)
200m	347	110kW	1	38,170
<250m	282	145kW	1	40,890
<300m	282	145kW	3	134,937
<350m	184	145kW	10	266,800
<400m	140	145kW	18	365,400
<450m	88	145kW	10	125,048
<500m	86	145kW	15	187,050
<600m	41	145kW	18	109,388
<700m	60	145kW	19	165,300
		230kW	7	96,600
<800m	1	145kW	35	5,075
				1,534,658kW

The question arises; Does 1535MW represent the maximum resource? Errors could have arisen in the modelling/map ratio and, as this was a map study, it is likely that some sites would, on visiting, be found to be unusable due to (a) habitations built since the map was published and (b) due to hedgerow trees or small copses not shown on the map. However, there are two reasons why 1535MW is thought to represent the lower, not upper, bound of the gross available resource:

1. It was not possible to apply any mathematical modelling to determine how much energy would be lost in a climate with a fairly evenly distributed windrose when wind turbines are sited further and further down the slope of the hill, or ridge of the site. This study is conservative in concentrating machines on, or near, the ridge or hilltop and

avoiding the hill slopes. The cost of energy table shows that on over half of the sites some loss of wind speed could be tolerated without the cost of energy exceeding 2.5p/kWhr.

2. Four map squares were examined which had a scale of 1:10,000. Sites were sought at this scale and compared with those already found at 1:25,000. On one map square, 31 machines positions were discovered in a site which appeared unusable at the 1:25,000 scale. On two map squares, the number of machines doubled those which appeared to be available at the smaller scale and on the fourth map square, one site was lost by comparison.

15.3.2 The Effect Of Landscape Planning Policies On The Achievable Resource

It is the responsibility of the planners to decide in which class of landscape and which combination of specific site characteristics is appropriate for wind turbines. 1535MW and 3153 million kWhrs per annum is the resource for all classes, but this would involve siting machines on about 43% of all possible sites in the county.

A common reason for refusing planning consent is the "overdevelopment of a site". ie crowding too many buildings into too small a space. It is for the planners to say what percentage of sites in the county could have wind turbine clusters without the "overdevelopment of wind energy in Cornwall". This is a subjective matter and there is no way in which we can know the final answer until that limit is reached. What is needed is an indication from the planners on their current view of the maximum number of appropriate wind energy sites for the county and what landscape class and other site promoter(s) they would favour. Then, the operators could present coherent applications for planning consent. This should be spelt out in the next amendment to the County Structure Plan by allocating a target number of wind energy sites in each landscape class (eg AONBs or AOGLV etc) with guidance to operators on the favoured site characteristics (eg with the base of the tower in a hedge, near existing ugly development, in a landscape which already has many vertical features etc), and which sensitive siting policies (ie as developed in chapter 9) would encourage a favourable response to planning applications. In this way, operators would be able to plan ahead for a known number of sites rather like the allocation of new houses or factory space.

The position of the actual sites for prospective wind turbine clusters depends on a number of detailed investigations beyond the scope of this survey and include:

1 The implications for the host electricity distribution system.

2. The attitudes of landowners, whether or not the land is owner-occupied or tenanted.

3. The disposition of common land and land with no paper title holder, restrictive covenants, or land subject to disputed ownership and any prescriptive rights which affect the site.

4. Access for construction, maintenance and underground services.

5. Whether or not the operator has compulsory purchase powers.

6. Site specific sensitive siting criteria particularly the question of dominance, and the effect of terrain shape and height on noise and windflow.

7. The securing of windrights and the likelihood of new forestry plantings.

8. Fire risk at the site from annual scrub burning and accidental or deliberate ignition.

9. The prevalence of vandalism and indescriminate shooting in the area.

10. Ground conditions and the likelihood of sub-subsidence or particularly on unpaved access routes.

It is the reponsibility of the turbine operator to sort out these problems most of which have to be solved before an application for planning could be filed. Much wasted effort and repeated consultation with the planning authorities could be avoided if the Structure Plan amendment is suitably framed. To aid this process and to show how different policy decisions would affect the resource, various scenarios are assumed. This is followed by a proposed target level of wind energy generation in Cornwall:

15.4 The Achievable Resource. Possible Planning Policies For Implementing Wind Energy

Policy A. From the total of 1511 sites deduct:

1. All sites with a separation distance of less than 300m from any habitation as these will largely be single machine sites which will not contribute very much to total capacity.

2 All sites in Areas of Outstanding Natural Beauty, in Special Areas of Great Landscape Value and in the Heritage Coast Area.

3. All sites where the cost of energy exceeds 2.5p/kWhr then:

Table 15.3 Resource Excluding AONBs

Separation Distance	No of Sites	Average No of Machines per site	Total No of Machines	Capacity MW
301 - 350m	84	10 x 145 = 1.45MW	840	121.8
351 - 400m	50	18 x 145 = 2.61MW	900	130.5
401 - 450m	31	10 x 145 = 1.45MW	310	44.9
451 - 500m	34	15 x 145 = 2.175MW	510	73.9
501 - 600m	20	18 x 145 = 2.61MW	360	52.2
601 - 700m	21	16 x 145 = 2.32MW	336	
		+ 6 x 230 = 1.38MW	126	
			462	77.7
>700m	Nil			
Totals	240	15 2.25MW	3382	501.1

Annual kWhr Output: >1300 million units.

This compares with Cornwall's maximum demand for electricity of 520MW and annual consumption of 2,270 million kWhrs ie it could account for 57% of Cornwall's kWhr demand.

Policy B An alternative strategy would also eliminate Class II landscape areas. See figure 15a. These include the Areas of Great Landscape Value, of Great Historic Value, of Great Scientific Interest. (The country parks, local nature reserves and Cornwall Trust For Nature Conservation sites have already been eliminated.) As above, we also exclude sites where the cost of energy exceeds 2.5p/kWhr and sites with a separation distance of 300m or less. This leaves the following resource:

Table 15.4 Resource Excluding All Designated Land

Separation Distance	No: of Sites	Average No: of Machines per site		Total No: of Machines	Capacity MW
301 - 350	51	10 x 145	= 1.45MW	510	73.95
351 - 400	28	18 x 145	= 2.61MW	504	73.08
401 - 450	17	10 x 145	= 1.45MW	170	24.65
451 - 500	19	15 x 145	= 2.175MW	285	41.32
501 - 600	13	18 x 145	= 2.61MW	234	33.93
601 - 700	9	16 x 145	= 2.32MW	144	
		+ 6 x 230	= 1.38MW	54	
				198	33.30
Totals	137	15	2.25	1901	280.23MW

Annual output: 735 million kWhrs. (32% of Cornwall's demand for kWhrs)

If we eliminated all sites except derelict or industrial land then the resource would be negligible.

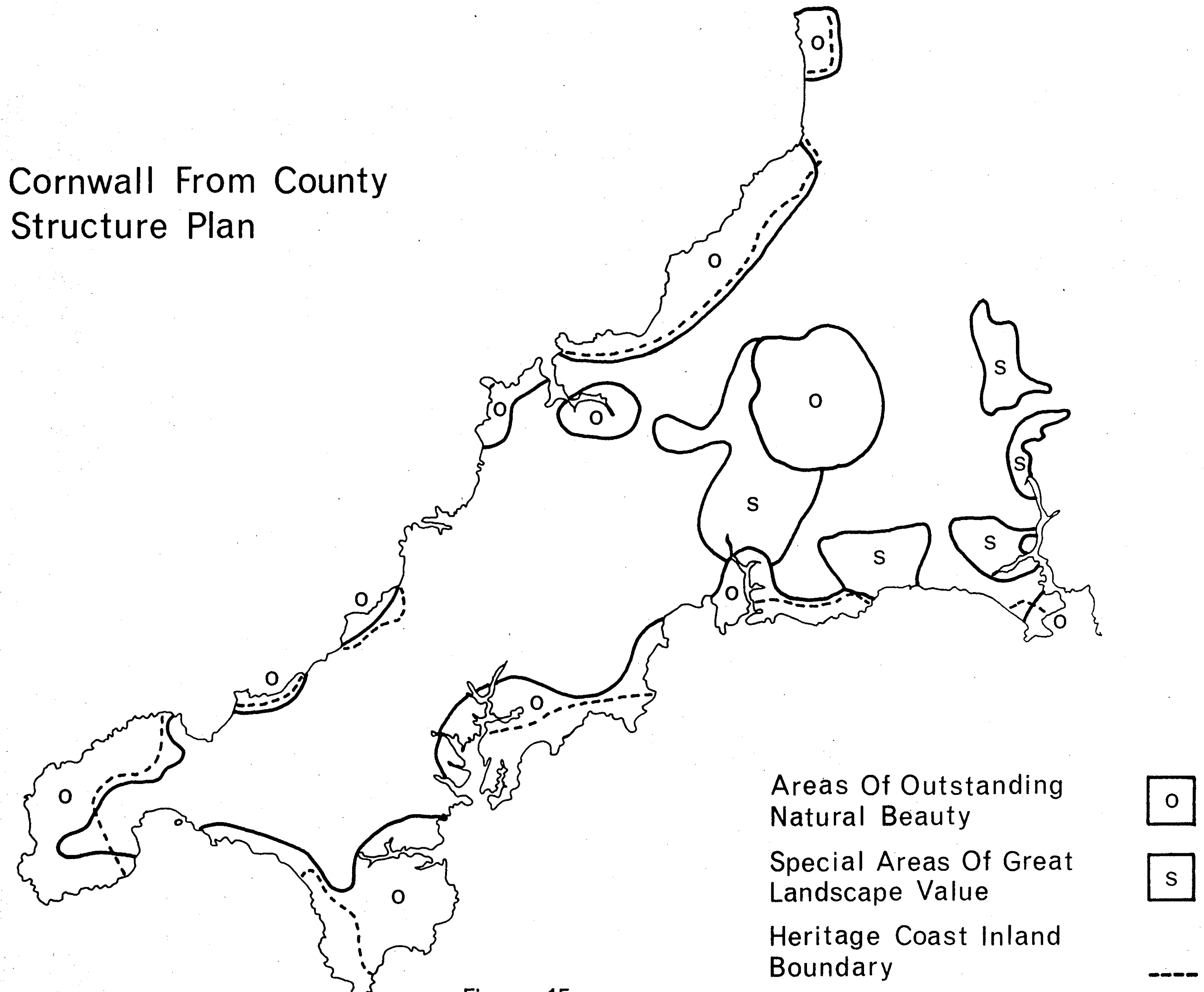
15.5 The Achievable Resource: Conclusion

The specifications of the type and size of plant chosen for Cornwall has a dramatic effect on the overall resource. This ranges from one, 2.5MW machine (which still fails to meet the District Councils noise criteria), to 1535MW made up from 15-22m, 125-230kW machines. The total resource for a given fixed number of sites is inversely proportional to machine size. This is the central conclusion of the study.

Although it may be theoretically possible to install 1.5GW of wind energy in Cornwall and every site, this degree of development is likely to be unacceptable on the grounds of saturation. Thus, possible strategies have been described which fine down the total resource to 500MW using 240 sites (or just 7% of the gross number of over 3500 sites in the county); or 280MW on 137 sites (or 4% of the total number of sites.)

In the final analysis the resource does not appear to be limited by technical, economic or environmental restraints as these apply to individual sites. However, a point may well be reached when to add significantly to the total number of wind turbines in the county will be resisted on grounds of saturation. We can only guess what number of sites this represents and uncertainty on this issue compromises any firm assessment of the achievable resource. Chapter 16 proposes a staged approach towards an estimated saturation level.

Cornwall From County
Structure Plan



Fiqure 15a

16. THE PROPOSED TARGET WIND GENERATING CAPACITY FOR CORNWALL

The conclusions and results of the study are now drawn together into a practical, staged, near term plan for the county:

Table 16.1 The Proposed Target Wind Generating Capacity For Cornwall

	Stage 1	Stage 2	Stage 3
PERIOD (approx)	1991-4	1995-7	1998-2000
Cumulative number of sites to be developed	<30	Approx 175	<350
Developed sites as percentage of gross number of sites in Cornwall	<1%	<5%	<10%
Cumulative installed wind capacity	>50MW	250MW	>500MW
Cumulative installed "diesel" capacity	90MW	Approx 525MW	As Reqd
Percentage of maximum demand	17%	Approx 100%	100%
Cumulative annual kWhrs wind output in millions kWhrs	150	Approx 650	>1300
Output as a percentage of 1985-86 kWhrs consumed in county	6.6%	28.7%	>57.3%
(Output from the "diesels" is not entered as this can be varied at will.)			(say 62%)
Number of turbines if each rated at 150kW	333	1666	3333
BY COMPARISON:			
Number of 11kV and 33kV wooden utility poles in Cornwall	63,649	----	----
Number of galvanised steel electricity pylons in county	Approx. 1400	----	----
Number of galvanised steel electricity pylons in England and Wales	Approx. 55,000	----	----
Number of wind turbines on four sites in California (1987)	Approx. 17,000	----	----
Number of wind turbines in Denmark (1988)	>2,000	----	----

The County Structure plan should approve Stage 1, and subsequent stages should be reviewed for approval when about two thirds of the previous stage has been achieved.

The above targets for wind installed capacity can be met whilst fulfilling the following environmental standards.

16.2 The Proposed Target Wind Generating Capacity for Cornwall: Sensitive Siting Criteria.

The proposals from this report are that horizontal axis machines of 10m or more in diameter will not normally be sited in the following areas:

Table 16.2 Sensitive Siting Standards

In a Class I landscape comprising an Area of Outstanding Natural Beauty, a Special Area of Great Landscape Value or on the Heritage Coast
Within 200m of any habitation
Within 1000m of any village
Within 2500m of any town
Within 5000m of any active airfield
On a Site of Special Scientific Interest
In a National Nature Reserve
In a Cornwall Trust For Nature Conservation designated area
In a Country Park designated area
Within 50m of an Ancient Monument
Within two diameters of any adopted road, railway or frequently used bridlepath, footpath, frequented place or any building unless this is associated with the operation of the turbine
Within 50m of any 32kV or within 100m of any >132kV transmission line
So as to dominate a war memorial
On a cherished hilltop or area
In a field where a hedge, confluence of hedges, drains, ditches, rough or disused land can be used instead
Where radio frequency interference problems are likely to result
In areas where there are particularly heavy bird populations

Turbines may be placed in other areas provided two conditions are met:

1. The wind turbine(s) is inaudible in the curtilage of any habitation or heavily frequented place during normal operating and atmospheric conditions.

2. The wind turbine shall not dominate any habitation by causing the top of the rotor disc to have an angle of elevation of 10 degrees or more when viewed from a non-cherished aspect of the house or its curtilage. This

angle of elevation shall be limited to 4 degrees when viewed from the main, cherished aspect of the habitation and from the main, cherished aspect of its curtilage.

District Council planning authorities may wish to consider imposing conditions on any consent for a wind turbine which embrace the following issues:

The colour of the installation
Limiting machines in any one cluster to one type and one size
Screening or landscaping for substations and site maintenance huts
Limiting the degree to which access roads are built on the site so as to prevent unsightly scars across hills
Removing or replacing machines which are unlikely to function again
The layout of a cluster of machines so as to present an aesthetically pleasing appearance which responds to the shape of the terrain when viewed from the most frequented directions
Limiting the maximum number of machines on any one site to avoid the appearance of clutter and muddle
Adequate standback distance from the most used roads or any railway which passes the site
Notification to occupiers of neighbouring properties of any site meeting regarding the proposal
Requesting that the operator who is applying for consent prepares an environmental impact statement
In pursuance of condition 1 above, to limit the measured noise levels at a position one tower height and one blade length downwind of the machine(s) to a sound pressure level which is calculated to ensure inaudibility at any surrounding habitation
Adequate restoration of the site in terms of reseeding
Fenced protection for any ancient monuments which may be close to the operational area.

It is hoped that District Councils can specify planning conditions with sufficient precision and effect so as to avoid the offering of temporary consents which are quite impractical for commercial developments of the high value contemplated.

17. CONCLUSION

The wind energy resource in Cornwall, and other parts of England and Wales with similar settlement patterns, is inversely proportional to individual turbine size down to about 15m diameter. The optimum turbine will be one designed specifically to be quiet, it will be between 17m and 19m diameter and will typically be installed in clusters of about ten machines giving each site a capacity of about 1.5MW.

POSTSCRIPT

A cynical reader may feel that the result of this study is compromised by the fact that it proposes to use machines of a size which the author's company - Windpower & Co (UK) Ltd - can produce.

This study started in August 1986 and finished in July 1988. The essential conclusions on the optimum turbine size were reached in December 1987.

A year earlier than this, in December 1986, Windpower started to prepare an application to the EEC for funding to build a 30m diameter, 430kW stall regulated wind turbine. This came about as a result of the perceived requirements of the size of machine favoured by European utilities and because there did not appear to be any major cost penalties in extending turbine diameter to this size.

Application for support to build a 30m diameter machine was made to the EEC in April 1987 in partnership with Concrete Utilities. This proposal was turned down in December 1987.

As a result of the conclusions of this study, a fresh application was prepared for the EEC in early 1988. The diameter of machine was fixed at 19.1m directly as a result of the findings on the optimum size of turbine decribed in chapter 15.

Dicit similiter facit.

APPENDIX

Specification of Windpower & Co. (UK) Ltd.'s 17.5m Diameter Wind Turbine at Treculliacks, Constantine, Falmouth

Rotor

Number of blades	3
Orientation	Upwind
Tilt Angle of Axis of Rotation	Upwind inclination of 4 degrees
Diameter	17.48 m
Swept Area	239.97 sq.m.
Rotor Centreline Height	15.6 m
Speed	39.6-40.1 & 59.4-60.5 r.p.m
Direction of rotation	Anticlockwise facing the rotor from upwind
Power regulation	Aerodynamic stall
Cone angle	Nil
Solidity	7.6%
Tip Speed	36.2-36.9 & 54.4-55.4 m/s
Design Tip Speed Ratio	5.9
Tip Speed Range	20 to 1.5
Design maximum power coefficient	.44 Rough surface with struts and straps
Strap/Strut attachment	At .54 of radius

Aerodynamic braking

Tips : 18.5% of radius. These turn to 90 degrees in a 45 degree helix. The tips stop the machine in winds of up to 20 m/s and slow the machine to 1-2 rpm for 20-40 m/s winds. The tips are turned to the braking position by centrifugal force and springs. They are armed into the running position by three hydraulic rams.

Hub

Type	Fabricated steel, fixed
Blade connection	Blade bolted inside double tapered steel box

Blade

Aerofoil mainblade	LS1 04XX
Reynolds Number	1.66 x 10 Exp. 6
Taper	Non-linear taper
Tip	Based on Hoerner No. 5
Pitch	Fixed
Twist	Non-linear
Aerodynamic centre (at design point)	)
Chordwise centre of gravity	) Coincident
Chordwise elastic centre	)

Main blade	Shell - E glass reinforced epoxy, foam stiffening in rear panel
Construction	Main beam - Coastal Douglas Fir vertically laminated, epoxy saturated and reinforced with high yield steel Torbar, i.e. reinforced wood construction
Strut	NACA 4421, polyester shell encasing Torbar
Strap	Stainless steel wire rope
Fairings	Glass reinforced epoxy
Blade fatigue life	Not limited
Maximum flapstress	8 N/sq mm at windspeed of 25m/s with turbine operating 12 N/sq mm at 72 m/s with turbine stopped
Flap Frequency	Mode 1 : 10.2 hz Mode 2 : 48.1 hz Mode 3 :123.1 hz (Measured)
Lead lag frequency	Mode 1 : 15.9 hz Mode 2 : 74.1 hz Mode 3 :189.7 hz (Measured)

Tower

Type	Tapered, twenty sided.
Height	14.5m from ground level
Weight	7 tons with hinge
Diameter	Tapered
Frequency	Mode 1 : 1.65 hz (Measured) Firm tower with Mode 1 between 2p and 3p (Measured) Mode 2 : 13.1 hz

Access	External ladder, plus suspended bucket for working on blades
Erection	Tilt up with gin pole fitted on hinge, without need for side guys, 20 tonne pull from winch.
<u>Foundation</u>	Reinforced concrete cruciform (in plan) 28 cu.m. volume, ends of cruciform each have two, 6.8m rock bolts - epoxy grouted into granite with lightning protection linking all reinforcing and terminating in 60m deep ground well.
<u>Transmission</u>	Hub of rotor is mounted directly on low speed shaft of gearbox. Parallel helical two stage gearbox with cast iron casing, no centreline split, close centres (280 mm)
Ratio	1:25.23
Output Speed	1500 - 1530
Efficiency	100% output - .98
	50% output - .9725
	30% output - .9675
	20% output - .96
	10% output - .9425
	5% output - .9
	2.5% output - .8
Wear rating	222 kW
Rating for braking	415 kW (5 times per hour)
Ultimate load	580 kw Short circuit load, once or twice in 20 years

<u>Generator</u>

A LC315M induction generator with three running conditions:

A 1000 rpm operation, wound in star, 25kW rating

B 1500 rpm operation, wound in double star with a 140kW rating

C 1000 rpm operation, wound in delta with a 90kW rating.

This gives the generator high efficiency at both part and full load, allows the turbine's rotor to operate near its maximum efficiency, reduces noise in the lower running speed and allows of continued operation at up to 40m/s wind speed.

Efficiency

Percentage of Full Output:	100%	75%	50%	25%
Condition A	93.5%	93%	91.4%	86%
Condition B	93.85%	93.94%	93.35%	89.5%
Condition C	94.17%	94.4%	93.9%	86%

Orientation

Entire nacelle rests on 1.2m diameter spur wheel via three Tufnol skids and centres on a 220m Glacier bearing to provide high inertia in yaw (adjustable by spring pressure). 2 off 2.35m diameter fantails drive the nacelle in yaw by 3905:1 gearing to provide a <2 degree accuracy of alignment.

1 right angle spiral level box 2:1.
1 right angle helical worm gearbox with ratio of 195.25:1.
1 pinion on spur wheel - 10:1.

High Speed Shaft Arrangement

Gearbox, 460 mm disc of disc brake, flexible coupling, cardan shaft, flexible coupling, generator.

Nacelle

Steel fabricated base with light steel sheet cover. The whole lined with rockwool/lead/rockwool for sound attenuation with air inlets and outlets via sound attenuating foam and lead lined labyrinth passages. Access via top hatch to working/monitoring space complete with tools and fire extinguishers.
Dimensions: 3.56 m long x 1.6 m wide x 1.6 m deep

Disc Brakes

300kW capacity twin calipers with equalising arms, sprung on, hydraulically released.

Operating Procedure

When the turbine is started the disc brake is released and the blade tips are drawn in. The machine will start to rotate at a wind speed of 1.7 m/s and will synchronise in six pole running at 2.2 m/s. This condition is maintained until the output exceeds 25kW for a preset time when the machine desynchronises and runs up to 4 pole operation and resynchronises. Power can now rise with wind speed until 140kW is exceeded for a preset time, or until a steep rise in power is noted. The turbine then releases its tips, slows down, draws the tips in, speeds up and resynchronises in the six pole condition which it can maintain in winds of up to 40 m/s. If in four pole running the power should fall below a preset value of about 20kW then the machine changes down to six pole operation. If windspeed falls below 2.0 m/s the set will desynchronise, but will continue rotating in winds of 0.5 m/s.

Protection

Rotor overspeed - 2 systems
Gearbox overtemperature and loss of oil
Vibration
Yaw error
Generator overtemperature - 3 R.T.Ds, one in each winding
Overcurrent
Reverse current
Phase balance
Earth leakage
Over or under voltage to G59
Over or under frequency to G59
Hydraulic overpressure (i.e. additional overspeed protection) and under pressure
High wind
Shear pins to allow tips to deploy if all overspeed protection fails

Remote Control

The wind turbine is wholly automatic in operation but also has the facility for remote, manual control and for remote monitoring. A Tandon personal computer is programmed to communicate with the turbine via BT lines. In this way the operator can over-ride the automatic control and order the machine to start, to stop and to change gear. The wind speed, output in kW, rpm and temperature of the generator can be monitored on the Tandon. When the turbine shuts down, then it calls any designated telephone number and alerts the machine's operator with the appropriate recorded message.

By calling the machine via the Tandon it is then possible to find the reason for the shutdown as each trip is shown on the screen.

Twice a day the Tandon automatically calls the wind turbine and collects the ten minute average and maximum values of wind speed, power, rpm and generator temperature recorded over the previous twelve hours.